# DEMONSTRATIONS IN MODERN PHYSICS

*By the same Author*

MODERN GLASSWORKING AND LABORATORY TECHNIQUE
(*Heinemann*)

# DEMONSTRATIONS IN MODERN PHYSICS

By

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# CONTENTS

CHAPTER PAGE

INTRODUCTION . . . . . . 1

I. THE CONDUCTION OF ELECTRICITY THROUGH GASES: 6

(1) DISCHARGE TUBES. . . . . . 7

(2) CATHODE RAYS AND POSITIVE RAYS . 15

(3) THE PRODUCTION OF HIGH VACUA BY MEANS OF CHARCOAL . . . . 16

(4) THE PRODUCTION OF HIGH VACUA BY MEANS OF THE DIFFUSION PUMP . . 18

(5) THE McLEOD GAUGE . . . . 25

II. DEMONSTRATIONS WITH THE DIFFUSION PUMP: 29

(1) THE DISCHARGE THROUGH AIR, HYDROGEN AND CARBON DIOXIDE . . . . 29

(2) THE PERMEABILITY OF PALLADIUM TO HYDROGEN . . . . . . 30

(3) THERMIONIC EMISSION . . . . 31

III. THE MEASUREMENT OF $\frac{e}{m}$ FOR ELECTRONS . 36

IV. POSITIVE RAY PARABOLAS AND THE MEASUREMENT OF $\frac{e'}{m'}$, FOR PROTONS . . . 43

V. THE TRANSMUTATION OF LITHIUM . . . 51

VI. THE BROWNIAN MOVEMENT . . . . 56

VII. MILLIKAN'S APPARATUS . . . . . 67

CHAPTER PAGE
VIII. RADIOACTIVITY : 81
(1) RELATIVE RADIOACTIVITY OF MINERALS . 83
(2) A MODEL SPINTHARISCOPE . . . 87
(3) PROJECTION TYPE CLOUD CHAMBERS . 91
(4) NUCLEAR TRACKS . . . . . 98

IX. X-RAYS : 102
(1) OPTICAL MODEL EXPERIMENT . . . 103
(2) LAUE SPOTS . . . . . 106

X. SPECTRA : 115
(1) THE GRATING SPECTROMETER . . . 117
(2) X-RAY SPECTRA . . . . . 122

*Names and addresses of firms who supply materials mentioned in the text* . . . . . 130

*Selected Bibliography* . . . . . 132

*Index* . . . . . . . . 133

# LIST OF PLATES

PLATE TO FACE PAGE

I. A.—Positive Rays Seen Streaming Through a Hole 5 mm. in Diameter in the Cathode of a Discharge Tube

B.—Electrode Sealed into Discharge Tube

C.—Positive Ray Parabolas . . . 10

II. Photographs of a Cathode Showing the Increase in the Width of Crookes' Dark Space as Air is Withdrawn from the Tube . . . . . . 11

III. A.—Cloud Chamber Tracks from Radium

B.—A Thorium Star

C.—Optical Pattern Produced with Four Crossed Gratings . . . . 104

IV. A.—Laue Spots of Rock Salt Obtained by Means of the Demountable X-ray Tube Described in the Text

B.—X-ray Spectra of Molybdenum Obtained by the Bent Crystal Method of Mlle. Cauchois Using the Demountable X-ray Tube . . . . 105

# ACKNOWLEDGEMENTS

THERE is much in this book that is directly derived from well-known standard works, to the authors of which I am duly grateful. Many of the methods of working which are recommended here have been brought into being as modifications of University or professional techniques. These have not so much been copied as adapted and simplified for the use of those who have to make do with such materials and tools as are available in an ordinary school laboratory. Where it is felt that a particular debt is owed to an author acknowledgement is made in the text.

My thanks are due in particular to my colleagues, Mr. G. H. Locket and Mr. J. Barlee, for their help in securing the photographs for the plates ; to Messrs. R. P. Bell, F.R.S., A. J. Mee, A. W. K. Ingram and M. Nelkon for carefully reading the MS. and making many helpful suggestions ; and to my publishers for their unfailing and courteous assistance.

*Harrow on the Hill* M. C. NOKES.
1952.

# INTRODUCTION

A GOOD many of the fundamental experiments which are described in text-books and which are of the greatest importance in the development of theory are classed by teachers as too difficult for reproduction in a school. But it must be remembered that the original researches of yesterday often become commonplace in the class-room after the lapse of a few years. Simplifications can be made, new materials become available, effects are found to be produced with the expenditure of much less energy than was originally thought to be necessary and the combined ingenuity of many workers may serve to facilitate the production of phenomena which were at first the fruit of an unique originality. The enterprising teacher should see what he can do.

This is a practical book in the sense that instructions are given in it for performing experiments, some suitable for demonstration to large audiences, others requiring the close attention of a single observer or a small group of observers. The experiments described here are usually classed as belonging to the realm of physics, but most of them are illustrative of modern views of the structure of matter and are therefore of interest to chemists also. If there is a theme running through the whole book, it is perhaps the attempt to illustrate the overwhelming body of evidence in favour of the discontinuity of matter and electricity. These ideas are accepted nowadays without question, but we do well to remind ourselves of the origins of our firmly held opinions and to produce such proofs as we can when called upon to do so.

A great many purely chemical experiments can be done by students themselves if time and space permit and ought to be done by them after a few years of laboratory training, although it is often the lot of chemistry students of school age to find that their practical work is restricted to qualitative analysis, titrations and a few organic preparations. Such work is valuable and important, but it should be varied when opportunity offers and an occasional demonstration which is beyond the ability of students to perform for themselves adds greatly to the interest of a course of instruction. After a few years of experience the teacher may be expected to have acquired a certain maturity of skill in practical manipulations which he should take pains to exercise and should extend himself in trying new demonstrations. The simpler experiments may be handed over to the pupils themselves, when the teacher is sufficiently familiar with the practical conditions to be able to give precisely those instructions which will ensure success. Such instructions are indeed given in some text-books, but in others the details are vague and points which are essential in making a demonstration a success are not referred to at all. The accumulated experience of laboratory methods and materials which the teacher comes to possess after a few years should be employed to broaden and enliven subjects whose presentation may become dull and stereotyped if he fails to break fresh ground.

The factors which limit the activities of the science teacher are lack of time and money, but with determination these limitations can be overcome. Time can always be found to do the things which interest us most and lack of funds, although more serious, is a challenge to our ingenuity. It is true that some new materials must be purchased, but there is always a good deal of old equipment in a laboratory which can be altered or adapted to new uses. Those who can handle tools find inexhaustible opportunities for the exercise of their skill in making what is required from scraps and oddments for which there is no other use. Above all, the teacher of chemistry should acquire some skill in the working of glass. It is not necessary to attain the standard of the professional, although much pleasure may be had from the successful manipulation of this material. It is more important that a serviceable piece of apparatus should be produced when it is wanted. Appearance matters less than efficiency. Even if only a few simple operations can be learned, the teacher will find himself possessed of far wider powers than before ; he can put suggestions into effect which are otherwise unrealizable and can often save a situation by a timely repair when a breakage may otherwise mean the abandonment of a demonstration.

The range of effects that can be produced in a school laboratory has been greatly increased in the last few decades by the employment of the new materials that have become available and by the ease with which high vacua can be produced. The new materials include glass, for the improvement in the quality of laboratory glass, and particularly the introduction of the borosilicate glasses, have made it relatively cheap and easy to produce vacuum-tight systems which were the province of the research laboratory a few years ago. The small sizes of borosilicate glass can be bent and joined by means of the ordinary air-coal-gas blowpipe flame, but time is saved if oxygen is available. If hard glass tubing more than 1 cm. or so in diameter is to be worked, the addition of oxygen to the flame is essential. The portable hand torch is a most valuable piece of equipment and the joining of tubes which are part of an apparatus supported on a frame should be practised by its aid. The joints are blown through a rubber tube held in the mouth, thus leaving both hands free. This is not at all difficult to do.

The production of high vacua is so important in physics to-day that vacuum technique is specified as an item in the examination syllabuses of both Oxford and Cambridge Universities. This subject may well be introduced into school work. The ingenuity of W. Gaede has satisfactorily solved the problem of obtaining vacua at all levels. The vacuum pumps of to-day, both vapour and mechanical, have been developed largely from his ideas. The diffusion pump is an instrument of fascinating simplicity and power. It is silent in operation and will continue to work without attention as long as heat is supplied to it. Its dimensions and design are not critical. It may be made of glass or of metal, but the transparency of glass is an advantage for the purposes of the teacher. There is a choice of working substances. All these factors combine to make the diffusion pump an instrument which should be in every school laboratory, not only for the sake of the physical principles it exhibits, but also for the sake of the work that can be done by its aid. Instructions for making a simple pump are given in the text. If skill permits, some of the designs of pumps to be found in the literature of vacuum technique might well be copied.

It is not necessary in most physical investigations to employ high vacuum vessels which must be sealed off from the pump. As a rule a demountable system is used, that is, one or more waxed joints serve in the construction of the vacuum system, the phenomena being produced while the diffusion pump is kept working. After the demonstration the apparatus may be taken apart. These pumps are of use for work on thermionic emission, positive ray parabolas, transmutation and the applications of X-rays. Much interesting work can thus be done quite cheaply, if a diffusion pump is available and provided that the rest of the apparatus can be constructed in the laboratory workshop.

So many new phenomena came to light in the last decade of the nineteenth century, with the work of J. J. Thomson and the discoveries of X-rays and radioactivity, that chemists were compelled to consider the extent to which the new ideas would affect their theoretical conceptions. It soon became clear that much confirmatory evidence for Avogadro's hypothesis was forthcoming and this cornerstone of chemical theory has only been more firmly seated by the new work. Some of the experiments described here have a bearing on the determination of Avogadro's number N. Another outcome of the progressive revelation of the structure of matter that these discoveries heralded was a change in the conception of valency, the clear enunciation of which is the central problem of chemistry, concerned as it is with the combining habits of the atoms. The importance of Moseley's work in confirming chemical classification and that of Aston in the independent measurement of atomic weights should certainly be emphasized by relevant demonstrations if possible. Several experiments have thus been included here because of their bearing on the structure of the atom and an effort has been made to copy such classical researches as the production of Laue spots and X-ray spectra with apparatus that can be made at a negligible cost. Other experiments have been included because they give the chemist alternative ways of presenting ideas to pupils which hitherto seem to have escaped the notice of demonstrators in schools.

## CHAPTER I

# THE CONDUCTION OF ELECTRICITY THROUGH GASES

As early as 1838 Faraday had made observations of a glass vessel from which most of the air had been withdrawn and through which an electric discharge was passed. He described the dark space that occurs between the glow surrounding the negative electrode and the remainder of the luminous gas. This region of darkness is still called Faraday's dark space.

About twenty years later Professor Plücker at Bonn was able to command the services of the exceedingly skilful glass-blower Geissler, who not only made glass tubes in which the discharge through gases at low pressures could be observed, but also made mercury pumps of glass which were capable of producing a better vacuum than any mechanical pump of that period.

A detailed study of the phenomena that occur in the discharge tube thus became possible and observations were made by Plücker at Bonn, by Hittorf at Münster and also by Goldstein and others. In 1869 Hittorf observed the sharp shadows cast at low pressures by obstacles placed in front of the cathode and hence explained the green or blue fluorescence seen on the walls of the tube as being due to rays which travel in straight lines. The term *cathode rays* was introduced to explain these phenomena by Goldstein in 1876 and is still in use to-day.

Sir William Crookes published his investigations of electrical discharges through gases at reduced pressures in 1879. The apparatus he designed showed many phenomena in a striking way, although most of them had been seen before in Germany. For instance, the dark space which separates the cathode glow from the cathode itself at certain pressures is usually called the Crookes dark space in this country, but it had been observed by Plücker in 1858 and is often known as the Hittorf dark space on the Continent. Nevertheless, the thoroughness of his investigations, the efficiency of the apparatus he designed and the style of his publications entitled Crookes to a high place in the regard of physicists. He did not prove that the cathode rays are negatively charged. This was done by Perrin in 1895 by allowing them to fall into an insulated box connected to an electrometer. It is now known that at pressures of the order of 0·01 mm. of mercury a stream of negative electrons, or cathode rays, is repelled from the cathode surface at right angles to it, and that the positively charged remnants of the gaseous particles in the tube are accelerated towards the cathode. These particles constitute the positive rays which can be seen behind the cathode if it is pierced with a hole, by reason of the light emitted when the positive particles collide with gas molecules. The light emitted is very feeble. See Plate I, A, facing p. 10.

## (1) Discharge Tubes

Few phenomena are more interesting to the beginner than those to be seen when a potential difference of a few thousands of volts is applied to two electrodes inserted in a tube from which the air is gradually withdrawn. A piece of glass tube of almost any length and diameter may be used if it is closed with well-fitting rubber bungs through which brass or copper wires pass and if means are provided for the withdrawal of the air. A glass stopcock attached to a narrow tube which passes through one of the rubber bungs will serve for connection to the pump, thus :

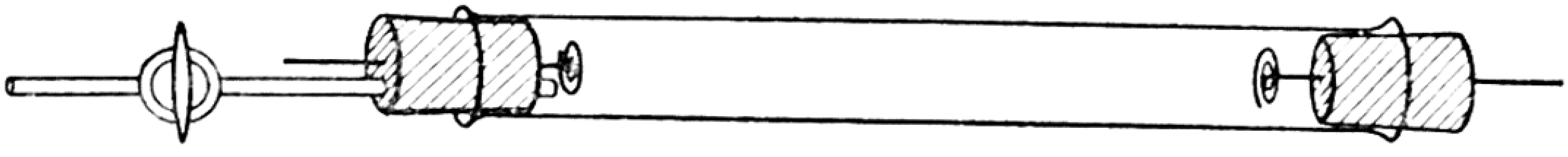


Fig. 1. A Simple Discharge Tube. The tube of the stopcock and the wires of the electrodes pass through tightly fitting rubber bungs.

A small induction coil giving a $\frac{1}{4}$- or $\frac{1}{2}$-inch spark provides the potential difference and a mechanical pump, say, of the Geryk type, will give a sufficient degree of evacuation for most of the phenomena to be displayed.

The apparatus can be much improved if some elementary glassworking can be undertaken. The stopcock may be attached at right angles to the tube, thus leaving the ends free for the introduction of the electrodes. These may be of stout aluminium wire wound into a flat spiral, or the wire may be secured in an aluminium disc by inserting it in a hole and punching the disc until the wire is tightly held.

Fig. 2. Aluminium Electrodes.

The stopcock is first attached to the main tube by means of an ordinary T-joint, care being taken to reheat the whole circumference of the main tube after the joint has been made and to anneal the glass. One end of the tube is then drawn down to a diameter just greater than that of the wire of the electrode. When the glass is cool one electrode is fixed in place with red sealing-wax or one of the vacuum waxes now available, such as Messrs. Edwards' W.E. Wax or Everett's Vacuum Wax. The other electrode is then placed loose in the tube, which is held slanting during the drawing down of the end into which the second electrode is to be waxed.

When a large tube is required for demonstration purposes, the manipulation of the glass during the drawing down process is much facilitated if a support is provided for the cold end. Two fibre wheels, each about 2 inches in diameter, are mounted on a vertical pillar. They overlap one another and are free to revolve. They will thus serve to support a tube of any length or diameter and will hardly impede the rotation of the tube in the flame.

It is much more satisfactory to make apparatus for the investigation of electrical conduction through gases with electrodes sealed directly to the glass. This is not difficult with modern materials. If soda glass is to be used, the wire may be copper-clad nickel-iron, called Dumet, or it may be one of the recently developed alloys sold under the trade names Nilo or Telcoseal. A sheath about 2 cm. long is drawn down from the same glass as that of the tube into which the electrodes are to be fitted. The wire should just slide into this sheath. The glass is then heated from one end, with continual rotation, until it has collapsed uniformly on the wire, excluding air as it fuses. A collar of solid glass of the same composition is then fused round the centre of this sheath and the wire is ready for sealing into the end of the discharge tube through a hole slightly smaller than the collar. There should be no re-entrants when the

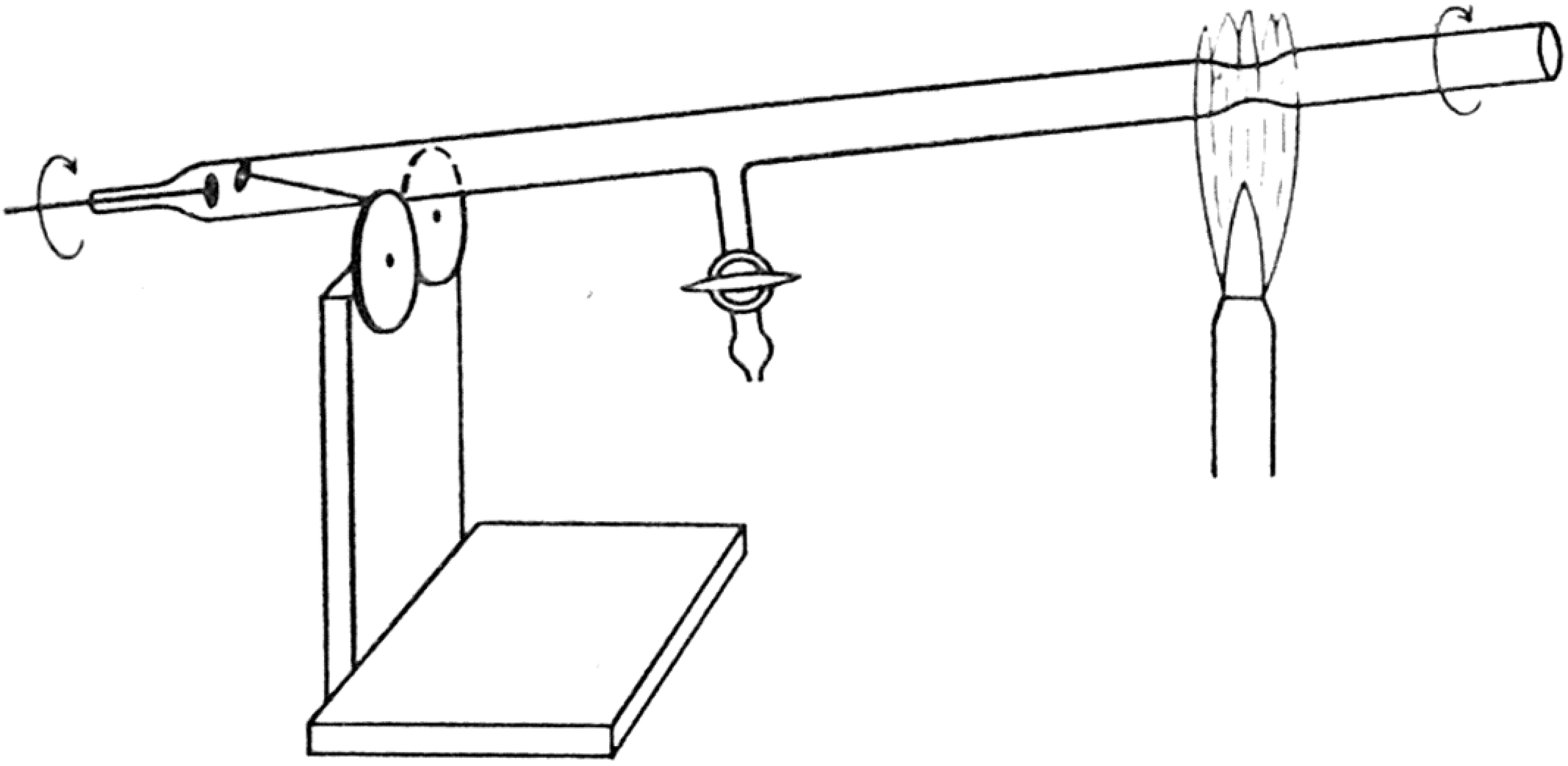


FIG. 3. Fibre wheel support for long glass tubes during glass working operations.

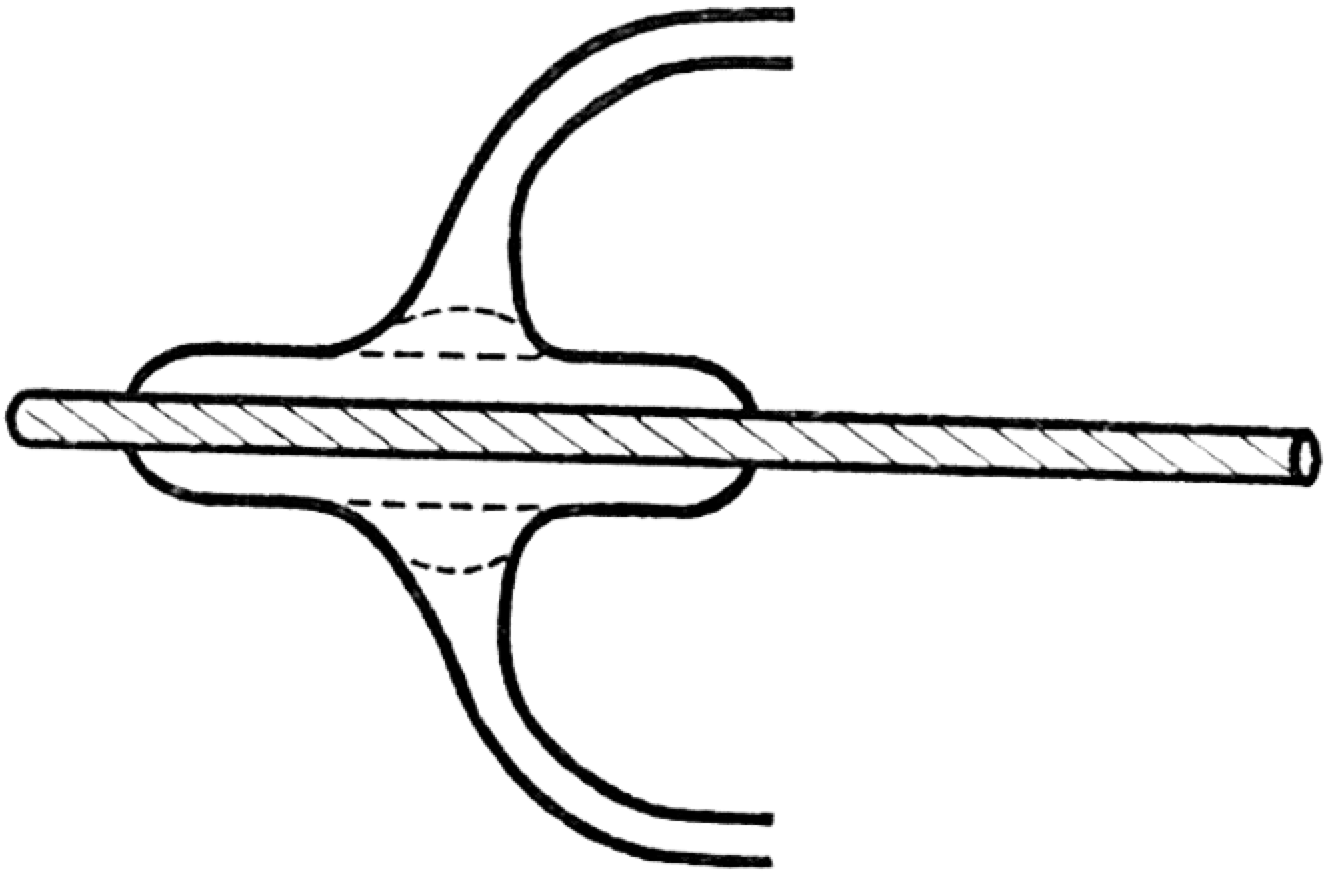


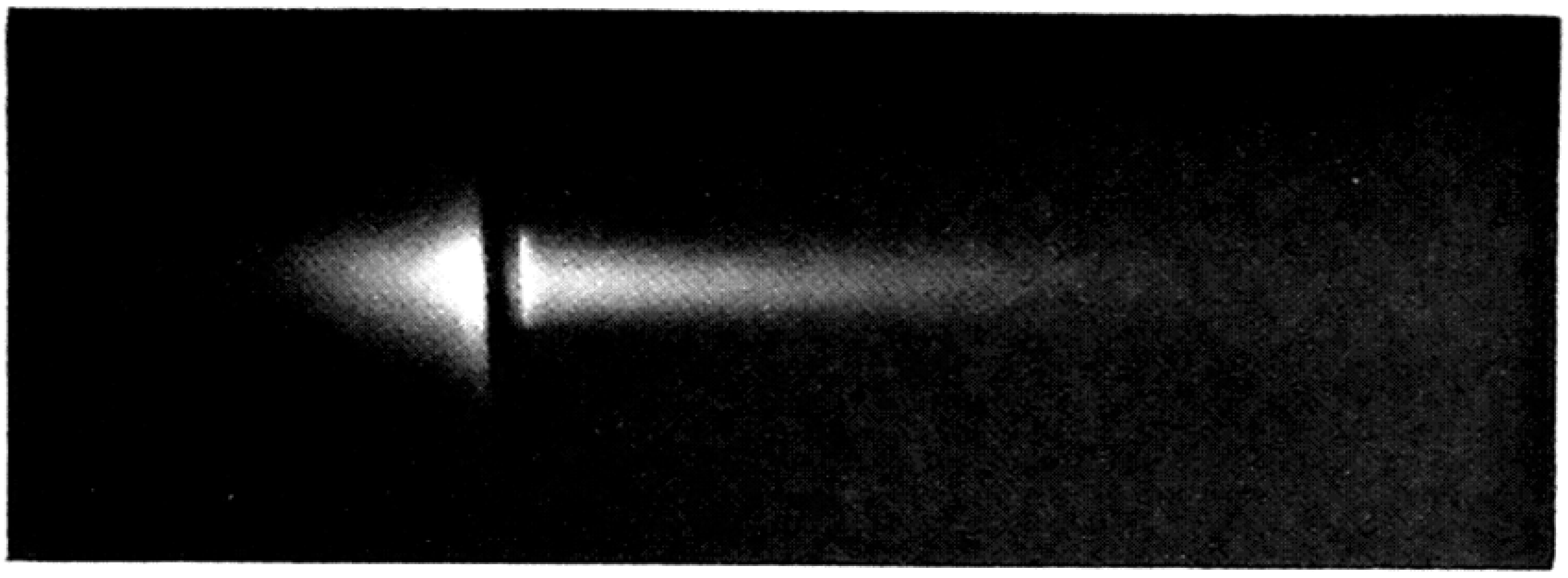
FIG. 4. Section through a well constructed metal-to-glass seal.

seal is finished. A good shape for a section through a seal of this kind is illustrated.

There should be no sudden changes in the thickness of the glass, but a good deal of practise will probably be required before results which would satisfy a critical glassblower can be obtained. It is well worth while to acquire some skill in sealing wires through glass as the construction of much modern apparatus depends upon this operation. See Plate I, B.

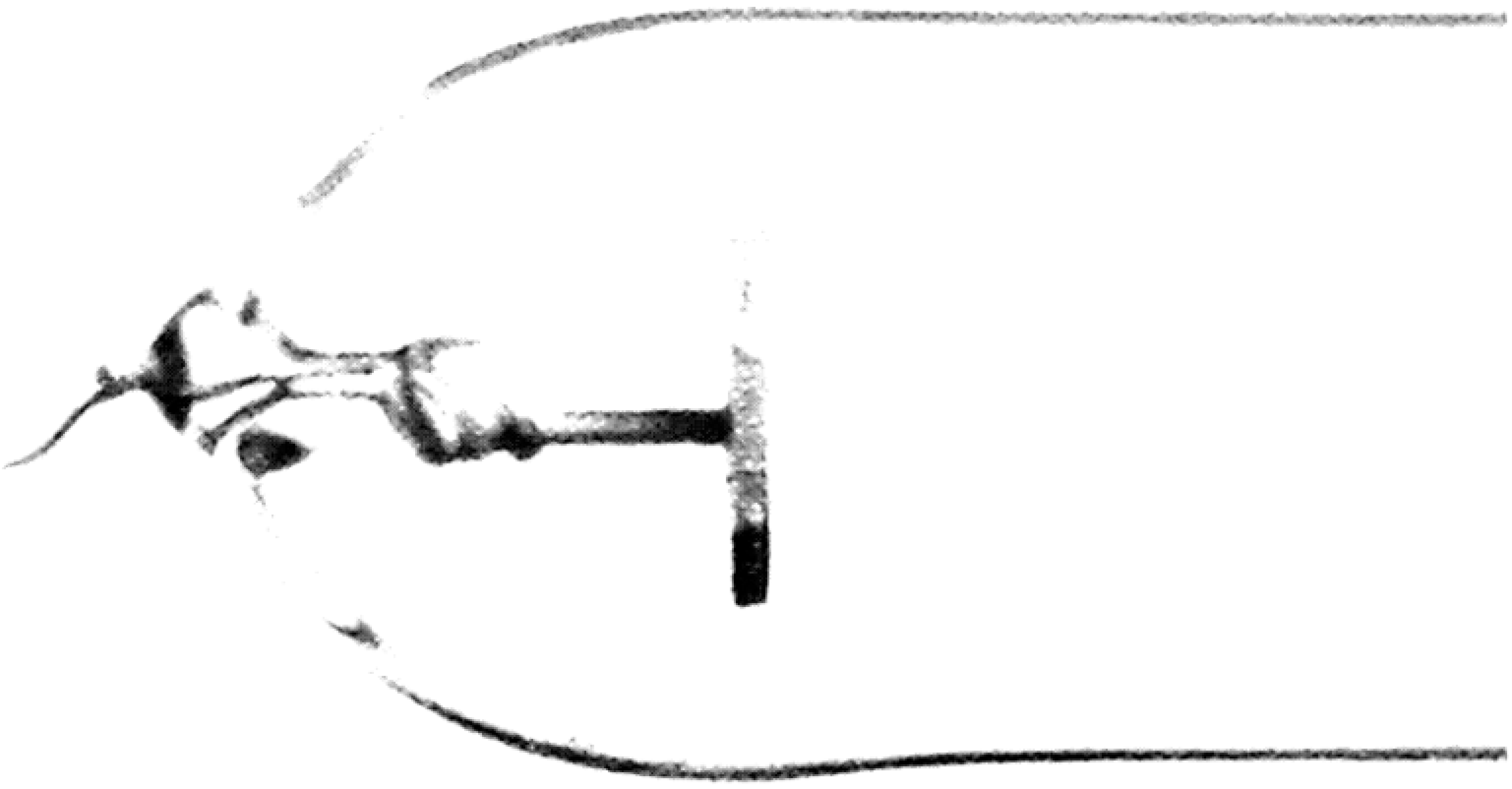
The use of borosilicate glasses is recommended for the construction of apparatus for demonstration purposes as it is easier to get durable results with it than with soda glass. Hard glass requires less time for heating up to the softening temperature from cold, is less likely to crack during the making of joints and is easier to anneal. Also, as it becomes fluid at a higher temperature than soda glass, it is less likely to become so fluid as to get out of hand and to give thick and unsightly patches. The disadvantages of using it are the necessity for an oxygen-coal-gas flame for working it and the fact that pin-holes do not readily close up even when strongly heated, but of course pin-holes may be removed by adding a drop of molten glass from a rod of the same composition as that of the tubing employed. Cracks usually seal up very readily, without extending. A worker who is used to soda glass will find that better results can be attained with hard glass, once the control of a blowpipe with added oxygen has been mastered. The oxygen cylinder should be fitted with a reducing valve giving fine control of the pressure of oxygen.

Molybdenum, tungsten and special nickel-chromium-iron alloys may be sealed to suitable hard glasses. They should be beaded with special sealing glasses, either Chance's GS3 or Intasil, or Messrs. Plowden and Thompson's Kodial, which are intended to be used as intermediates for sealing these metals into borosilicate glasses. Perhaps the most satisfactory type of seal into Pyrex or Hysil for the non-professional to make is that with a molybdenum wire and a Kodial sheath. This combination has been found to give a higher proportion of trouble-free joints than any other. Success depends upon the



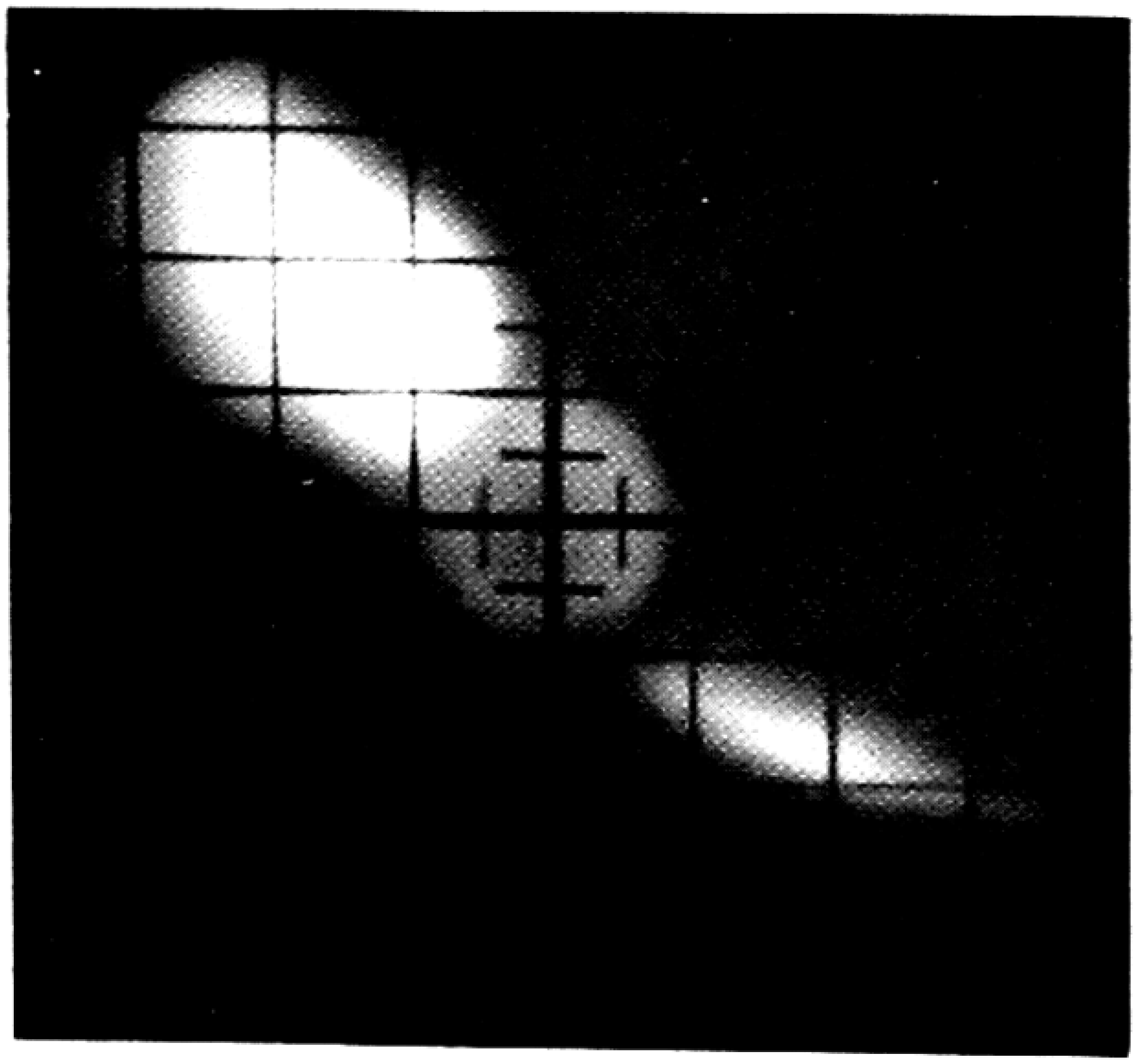
*Photograph by J. Barlee.*

A. POSITIVE RAYS SEEN STREAMING THROUGH A HOLE 5 MM. IN DIAMETER IN THE CATHODE OF A DISCHARGE TUBE.



*Photograph by J. Barlee.*

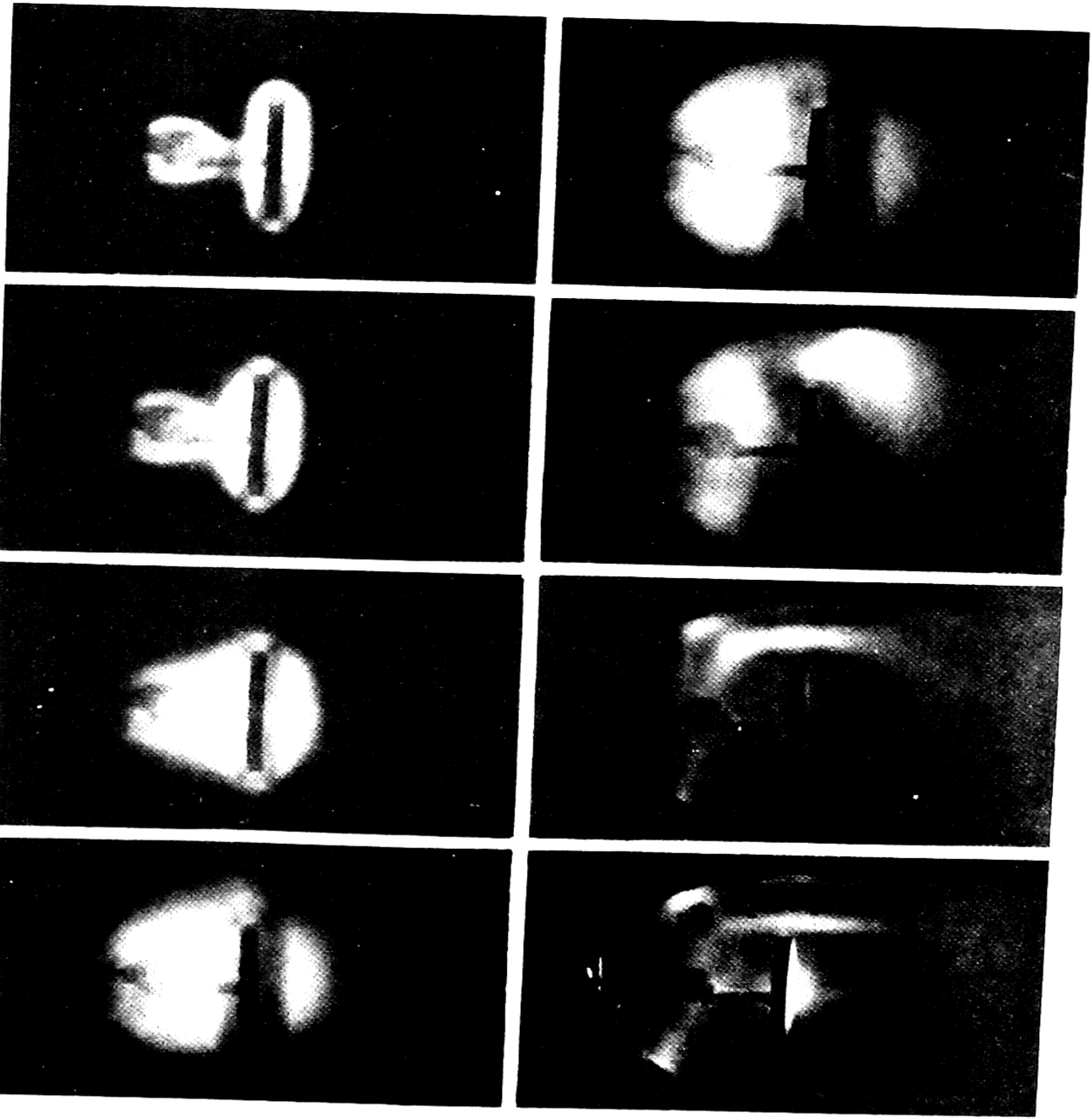
B. ELECTRODE SEALED INTO DISCHARGE TUBE.



*Photograph by J. Barlee.*

C. POSITIVE RAY PARABOLAS.

PLATE II



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care with which the prescribed steps in the process are carried out. Wires of 2 mm. diameter or more can be sealed into hard glass if the correct procedure is adopted.

The molybdenum wire is cleaned by dipping it for a few seconds in molten potassium nitrite. Only a small amount of the salt is required if it is fused in a hard glass test tube of dimensions 5 cm. × 8 mm. or so. The wire is then washed in distilled water and allowed to dry. It should not be touched with the fingers. The sheath of Kodial glass which has already been prepared is fused in place by careful heating from one end so as to exclude all air bubbles and a collar of the same glass is added. The wire may be held throughout these operations in a pin-vice. The cleaned end of the wire is then heated and coated with fused aluminium, to which the aluminium wire of the electrode is attached by fusion with a fine-pointed blowpipe flame. The procedure for inserting the electrodes has already been described.

When the discharge tube has been completed, the side tube is connected by rubber pressure tubing to a mechanical pump and the electrodes are connected to an induction coil. Most schools possess a Geryk pump which, when new, is stated by the makers to reduce the pressure in a closed vessel to $\frac{1}{50}$th of a millimetre of mercury. A worn pump of this type, or one in which the oil has not recently been changed, will still give a pressure of a few tenths of a millimetre. It is a good plan to attach an empty glass bottle on the intake side of these pumps to prevent an accidental influx of mercury, which attacks the brass cylinder. Care should also be taken when the pump is used in a chemical laboratory that chlorine is not allowed to enter it. With fair treatment a Geryk pump will give good service for many years. The oil should be renewed from time to time, according to the amount of use. The oil level in the space above the exhaust valve should be maintained so that the oil will just flow out when the screw plug is removed. This type of pump can be used as the fore-pump for mercury and oil diffusion pumps of the type that have two or more jets in series.

If a scraping vane mechanical pump of the Gaede or Hyvac type is available lower pressures can be reached and the operator is relieved of the labour of pumping by an electric motor. Although the smaller sizes of these pumps are not very fast they are most reliable and give a very good degree of exhaustion. Provision for the removal of water vapour from the system that is to be pumped should always be made when using oil pumps in high vacuum systems, as the ultimate vacuum is much improved if the oil is kept free from water. The most efficient and convenient drying agent is phosphorus pentoxide. A thick-walled glass vessel such as a Buchner flask or a Winchester quart bottle may be used between the oil pump and the system to be evacuated, or demountable tubes may be employed so that the phosphorus pentoxide can easily be renewed. Two designs of these tubes are shown which involve only simple glass blowing. They can be purchased from Messrs. W. Edwards & Co. Ltd.

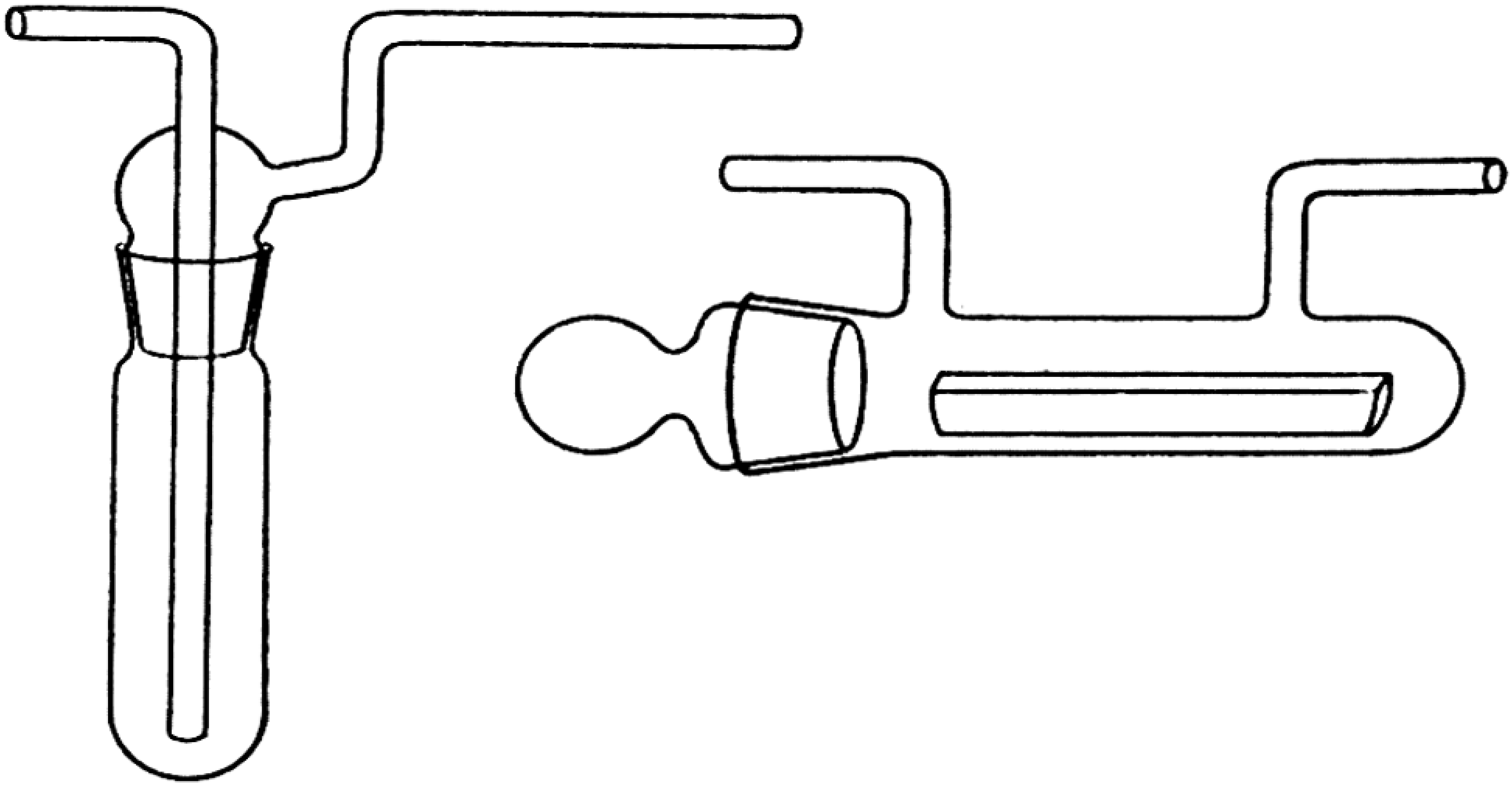


FIG. 5. Demountable phosphorus pentoxide tubes constructed so that the drying agent can easily be renewed.

It is a great help to a demonstrator using discharge tubes to have the high tension wires coming vertically down to his apparatus with the batteries and induction coil some feet away from the evacuated tube. This can easily be arranged by carrying the high tension wires on an overhead wooden framework, either supported by a tall retort stand or hanging from a beam. The wires should be separated from one another by 6 or more inches and may be connected to the evacuated tube by No. 32 S.W.G. copper wires, which are sufficiently soft and flexible to avoid the imposition of any strain on electrodes sealed through glass.

The phenomena to be seen in the discharge tube during evacuation have frequently been described and should be known by all students. At a pressure of about 20 mm. of mercury with air in the tube, thin reddish-violet streamers appear when the high potential is applied, taking irregular paths from one electrode to the other. As exhaustion proceeds they form a single diffuse bundle which later expands laterally and apparently fills the tube, except for a space near the cathode, which is called Faraday's dark space. The cathode is now seen to be outlined with a thin violet luminous layer called the cathode glow. At a pressure of about 1 mm. of mercury a dark space appears between the cathode glow and

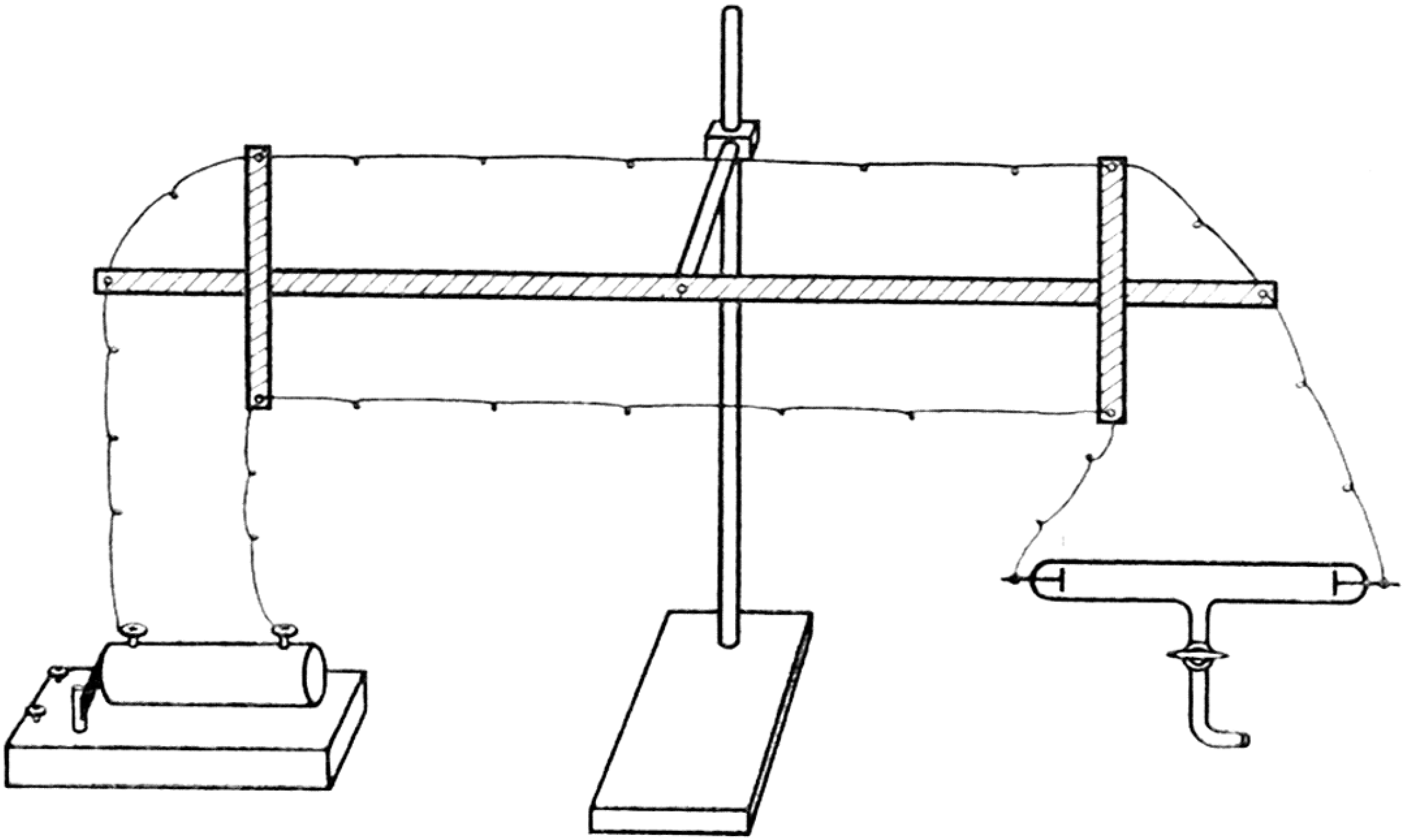


FIG. 6. A convenient arrangement of high tension wires for demonstrations with discharge tubes.

the electrode. This is Crookes' dark space and its size may be taken as a rough measure of the pressure of gas in the tube, for it increases in width as the pressure is reduced (see Plate II). Most of the light given out by the glowing gas comes from the reddish positive column, which is usually broken up into flickering disc-shaped or lenticular sections, called striations. As the pressure is further reduced and Crookes' dark space grows, the cathode glow becomes more diffuse and the reddish positive column retreats towards the anode. A Geryk pump will not as a rule reduce the length of the positive column to less than one half of that of the tube, but further exhaustion with a Hyvac or a diffusion pump will remove the whole of the positive column, which at this stage usually becomes bluish-white owing to the presence of water vapour and hydrocarbons. When Crookes' dark space fills the whole tube the walls fluoresce with a yellowish-green light if the tube is of soda glass, but the colour is more blue-green if a borosilicate glass has been used. The pressure is about $\frac{1}{100}$th of a millimetre of mercury at this stage and is often called an X-ray vacuum, as the fluorescence is produced by electrons striking the walls of the tube with the simultaneous production of X-rays. Further removal of gas renders the tube less and less conducting until at pressures of the order of $10^{-3}$ mm. of mercury no discharge will pass unless very high potentials are applied.

The electrical conditions inside a discharge tube have been very fully investigated by J. J. Thomson and others, but a complete explanation of all that occurs has not been agreed upon. Measurements with a probe at different points between the electrodes have established that neither fall of potential nor field strength is uniform. There are undoubtedly clouds of charged particles, or ions, in the neighbourhood of the electrodes, constituting space charges. Nor is there any doubt that electrons are repelled normally from the cathode surface, thus accounting for the cathode fall of potential by the presence of a positive space charge a little way from it. A smaller anode fall of potential is also due to a negative space charge in the neighbourhood of the anode.

### (2) CATHODE RAYS AND POSITIVE RAYS

In order to demonstrate the existence of both cathode rays and positive rays a tube may be constructed with two disc electrodes, each having a hole in the centre of diameter about 2 mm. The electrodes should be 5 or more cm. from the ends of the tube, which may be 40 or 50 cm. long and 3 or 4 cm. in diameter. One end of the selected tube is closed with a uniform hemisphere and the side tube for exhaustion is attached, on the opposite side to which two small protuberances are blown to accommodate the wires which carry the electrodes, thus:

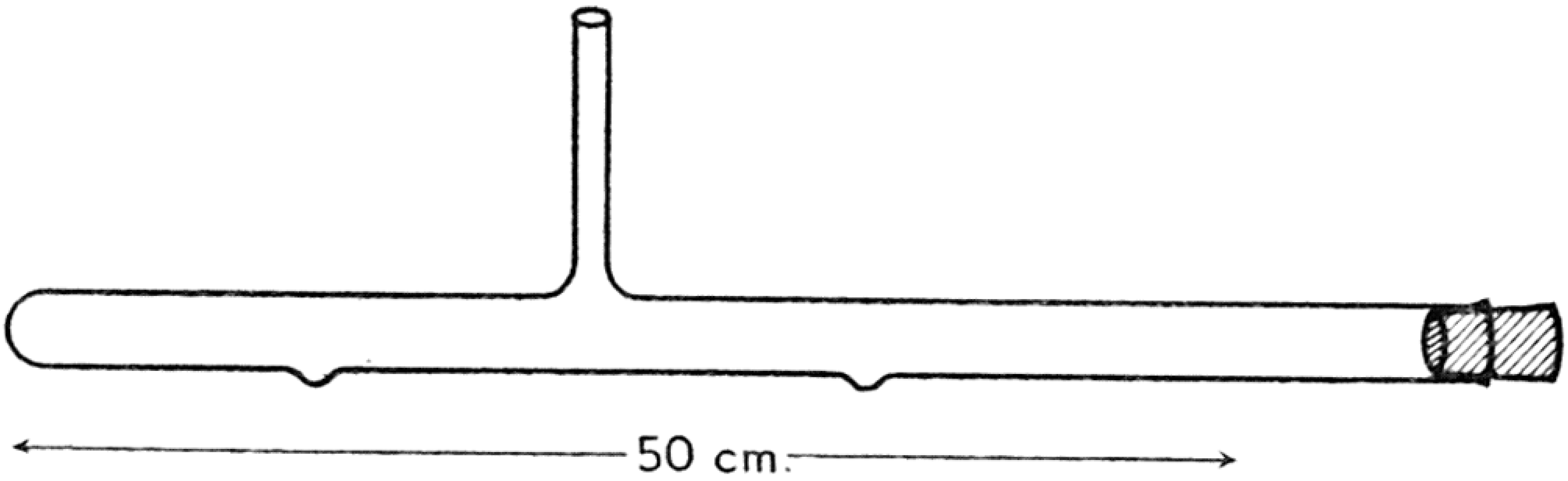


FIG. 7. An early stage in the preparation of a positive ray tube.

The electrodes are now constructed and may be made of sheet nickel welded or silver soldered to the sealing wire, or may be simply attached to a ring of wire by means of tags. Sheet aluminium may also be used for the electrodes and is easy to work. The diameter of the electrodes, together with the sealing wires attached to them, must be such as to allow the electrode to be manœuvred into position when the summit of the protuberance is pulled out and cut off to allow the sealing wire to protrude. The wire should be bent into the arc of a circle to allow for this operation. The wire should be held in pliers during sealing.

The second electrode is treated similarly and the open end of the main tube is then drawn down and sealed hemispherically to give a symmetrical appearance. If the wire seals are found to leak they may be reheated and blown again, especially if the tube is of hard glass. Alternatively, the tube can be made serviceable by the application of a little W.E.3 wax to the neighbourhood of the leak. When such a tube is pumped to a pressure of about 0·01 mm. of mercury there is visible only a faint whitish discharge between the electrodes, but a greenish luminous spot, not much larger than the hole in the electrodes, is visible on the end of the tube behind the anode. This is due to cathode rays. At the same time a faintly luminous column is seen to extend behind the cathode. It may not reach the wall of the tube and is not always easy to see. It is due to the recombination of ions formed by collision of the positive rays with gas molecules in the space behind the cathode. This is an important demonstration. It is worth while to go to some trouble to make positive rays visible to students. (Plate I, A.)

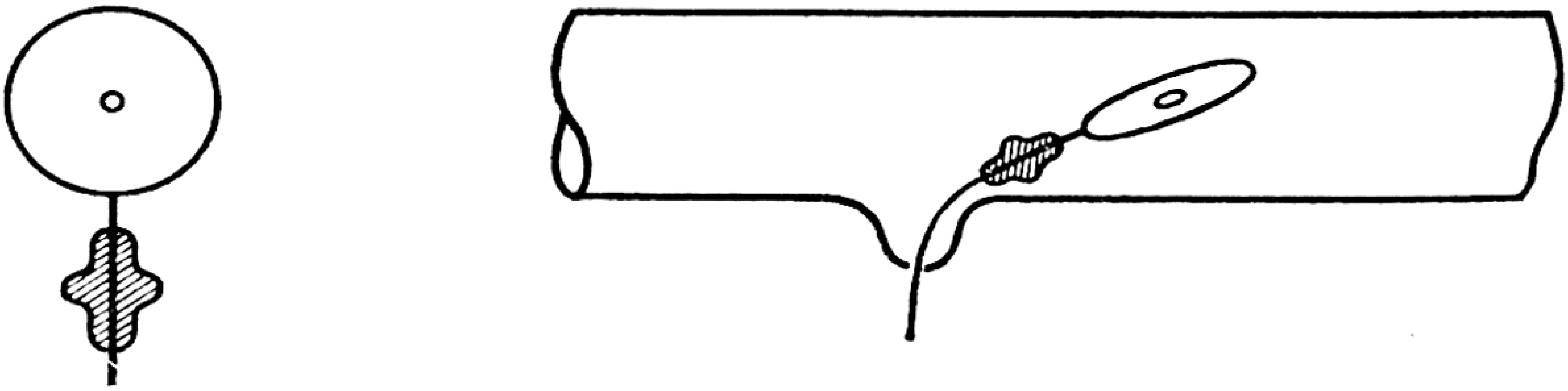


Fig. 8. Construction of disc electrodes and the method of inserting them in a positive ray tube.

### (3) The Production of High Vacua by Means of Charcoal

It is interesting to see the rapidity with which residual gas can be withdrawn from a discharge tube by means of charcoal cooled with liquid air. A discharge tube about 30 cm. long is constructed and is sealed to another tube at right angles which contains charcoal prepared for the absorption of gases. The charcoal tube is about 10 cm. long and is so constructed that a Dewar flask of liquid air can be brought up to it from below. The system is evacuated with a Geryk pump, the charcoal being gently heated with a soft flame to remove most of the gas it has absorbed. When the charcoal tube is cold, dry carbon dioxide is admitted to the system at atmospheric pressure and the pump is reconnected. Most of the carbon dioxide is now pumped out, but when the pressure is a few tenths of a mm. of mercury, as is shown by the conspicuous greyish-white colour of the positive column when the induction coil is turned on, the tube system is sealed off at a previously made constriction in the side tube connected to the pump. The apparatus is now set up as illustrated :

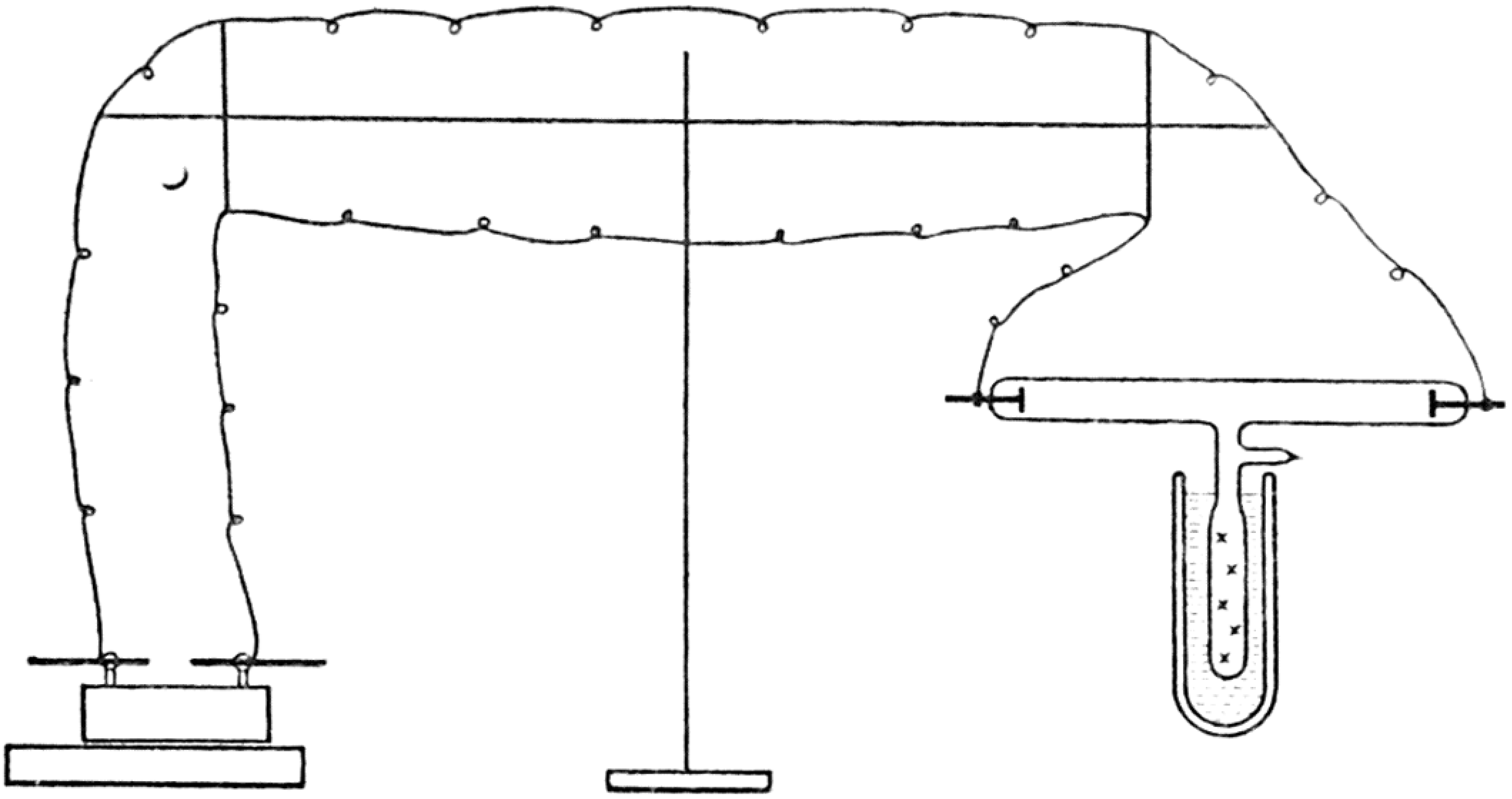


FIG. 9. Arrangement of discharge tube for showing the production of high vacuum by means of charcoal cooled with liquid air.

The length of the spark gap of the coil is such that a spark will easily pass when the secondary is disconnected from the discharge tube. The coil is turned on and the discharge passes through the carbon dioxide, but when the charcoal tube is immersed in liquid air the carbon dioxide and any residual air are rapidly absorbed and the gas pressure soon falls below that at which conduction can take place. The discharge occurs at the spark gap of the coil instead, showing that a vacuum of the order of $10^{-3}$ mm. of mercury, or better, has been produced.

### (4) THE PRODUCTION OF HIGH VACUA WITH DIFFUSION PUMPS

A good many demonstrations require a higher vacuum than that which can be obtained with the usual mechanical pumps such as those that are available in schools. The diffusion pump is so important an instrument, both in industry and in research, that the sooner students are introduced to it the better. The principle on which it works is extremely simple. A stream of vapour emerges from a jet and entrains gas molecules with it. The vapour is rapidly condensed, but the backward diffusion of the gas molecules is largely prevented by the oncoming stream of vapour. If the gas molecules are removed by a second pump, say of the mechanical type, this process results in the production of a high vacuum in any closed vessel which is connected to an orifice behind the jet. Very great pumping speeds can be attained, but, since at the low pressures produced the mean free path of the gas molecules is of the order of centimetres or more, the tubes connecting the pump with the vessel to be evacuated must be of large diameter, usually 20–30 mm., if advantage is to be taken of the high pumping speed. Diffusion pumps are capable of removing condensible vapours such as water vapour and hydrocarbons as well as permanent gases, so that very high vacua can be attained provided the right conditions prevail.

A small metal diffusion pump can be purchased for £12–£15, but it is instructive to make one of glass if time and patience permit. Many designs have been tried, with the object of increasing speed or in search of other advantages. The working substance may be mercury, dibutyl phthalate, Apiezon oil, Octoil, silicone oil, or some other substance of low vapour pressure at room temperature. The pump may be made of metal, glass or silica. Cooling may be by sealed-on water jacket, by water circulating through a coil of compo or rubber tubing, or by metal fins. Heat may be supplied externally by a gas flame or by electricity. An electric heater may be immersed if the working liquid is a non-conductor.

For the purpose of construction and demonstration in a school, hard glass is perhaps the best substance of which to make the pump. A design is suggested which involves only the easier glass blowing operations, but it will not be possible to make a pump at all unless an internal seal can be made successfully. Let it be assumed that mercury is to be used as the working substance and that the pump is to have two jets in series. A small conical flask of 100 c.c. capacity will serve as the boiler. A glass tube of the same diameter as that of the neck of the flask, say 18–20 mm., is sealed on to carry the mercury vapour to the jets. A 10 cm. length of narrow bore tubing, say 4 mm. in diameter, is sealed on at the base of the neck thus :

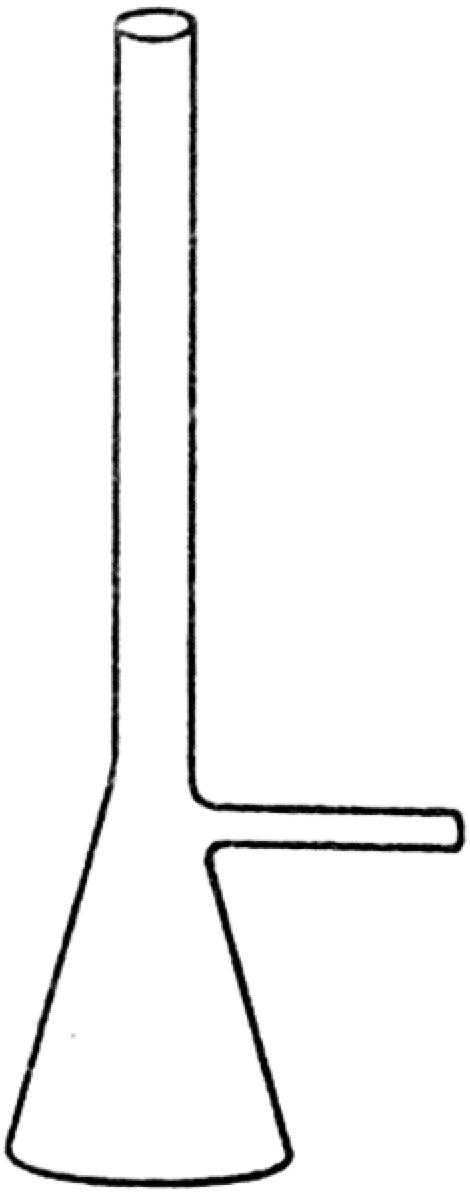


Fig. 10. First stage in the construction of a simple glass diffusion pump.

The jets are constructed of thin walled tubing. Two or three holes in the inner tube supply the glass umbrella with vapour. This jet may be 12–15 mm. in diameter and is of the expanding type. The lower jet is not more than 3 mm. in diameter and works in a constriction. An annular clearance of 2–3 mm. should be allowed. The jets are attached to a tube of the same diameter as that which supplies vapour from the boiler and are sealed into a wider tube as shown in Fig. 11, the lower and upper ends of this tube being blown out into bulbs which carry side tubes. This assembly is then joined to the boiler tube and is bent to bring the jets parallel to the uptake tube. The last joint is made in the narrow mercury return tube at A.

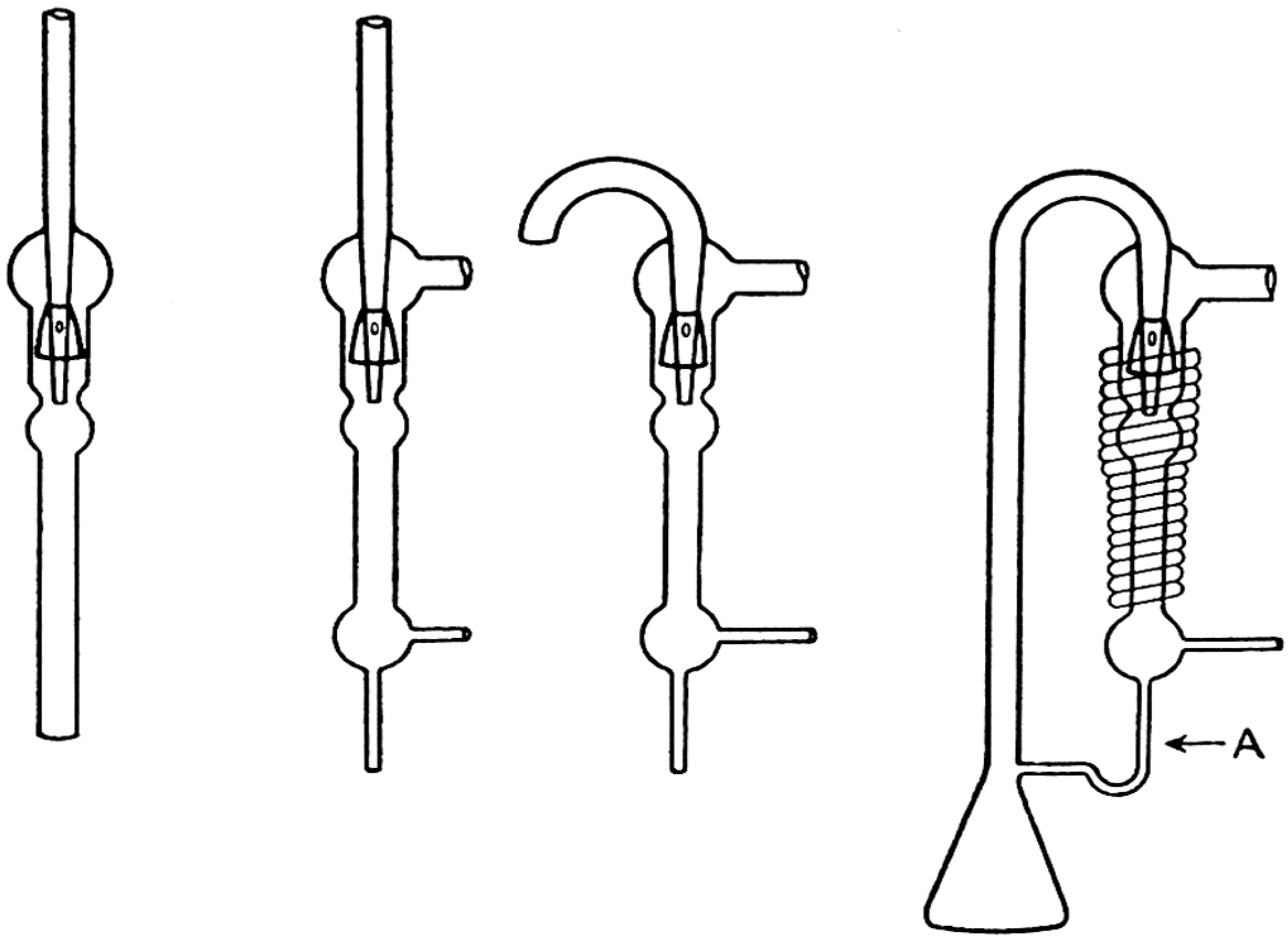


FIG. 11. Further stages with construction of a 2-jet glass diffusion pump.

The boiler and uptake tube are lagged with asbestos, which may be put on wet in order to give a close fit. Subsequent drying in an air oven will give the asbestos a permanent set. The downtake tube is coiled round with thin-walled rubber tubing through which cold water circulates. Before use the pump should be carefully cleaned out with chromic acid mixture, repeatedly washed with distilled water, heated to 110° C. in an air oven and the air withdrawn with a pump while the glass is still hot. Air dried by means of a calcium chloride tube may now be allowed to enter. A charge of 20 c.c. of clean vacuum-distilled mercury is inserted and the pump is ready for use. One waxed joint may be used on the high vacuum side if the highest vacua are not required, but an all-glass system is preferable. The connecting tubes on the high vacuum side should be as wide and as short as possible. The fore pump connection should be made to a thick glass reservoir of about 2 litres capacity, such as a Winchester bottle or a Buchner flask. The reservoir should have a layer of phosphorus pentoxide on the bottom to keep the system free from water vapour. A good quality tap should be fitted and beyond it a narrow branch tube with another tap for letting down the vacuum when required. The recommended arrangement is illustrated :

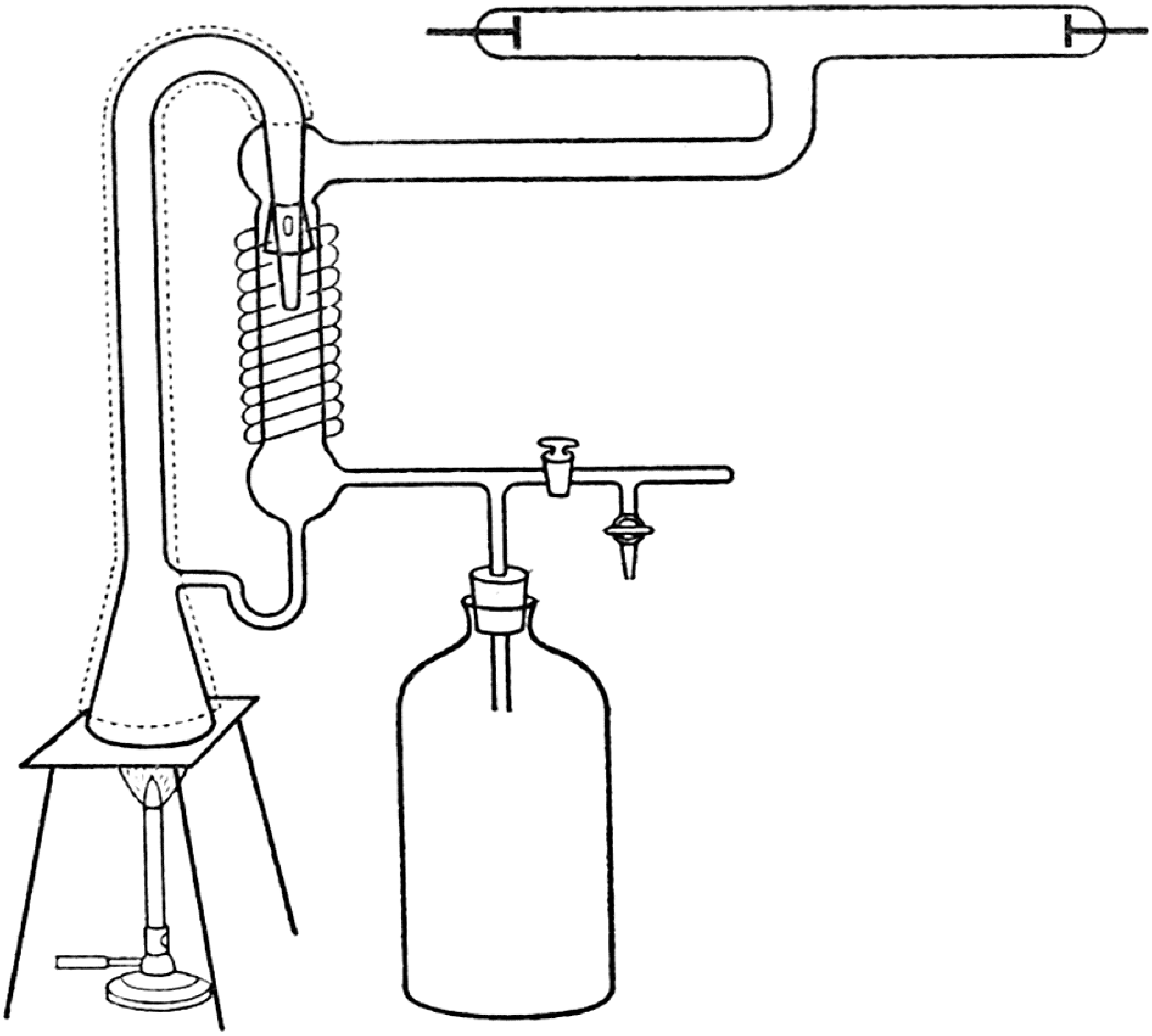


FIG. 12. Arrangements of reservoir between the diffusion pump and the fore-pump. A layer of phosphorus pentoxide should be put at the bottom of the Winchester quart bottle.

With this simple system the discharge tube will never be free from mercury vapour unless a liquid air trap is interposed between it and the pump. Mercury vapour is not objectionable in some continuously pumped systems, but it is harmful to heated filaments and cannot be allowed in photoelectric cells. Of course, the highest vacua cannot be attained in its presence. Many of the difficulties introduced by the use of mercury pumps are overcome by the use of oil as the working substance. A design of pump which works well with silicone oil will now be described.

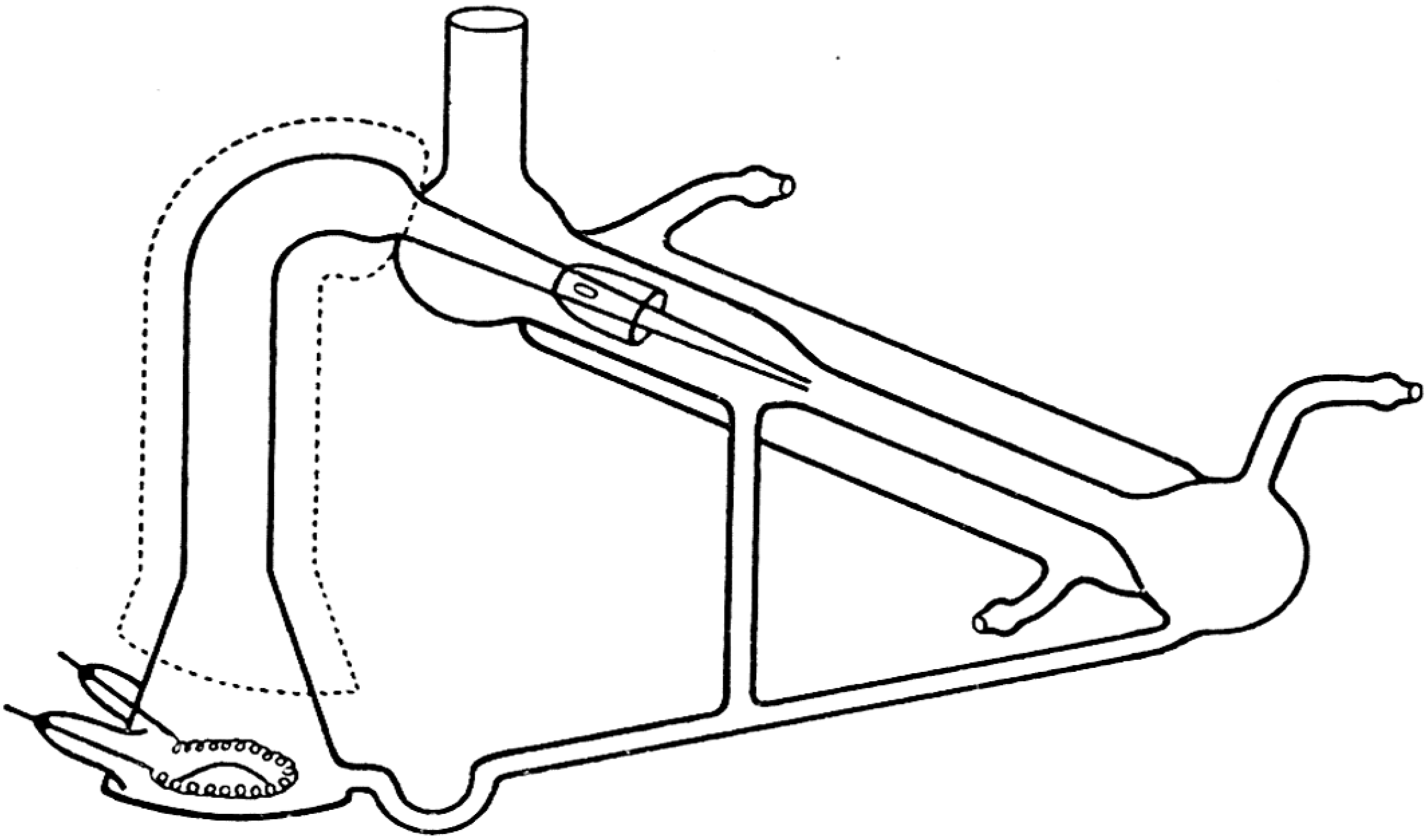


FIG. 13. Two-stage glass diffusion pump with sealed water jacket and immersion heating for use with silicone oil.

The features of this pump are the sealed-in water jacket and the immersed electric heater. The pump is compact and robust. It is quite fast enough for the continuous evacuation of the apparatus to be described and, as it uses a silicone oil, it does not require a liquid air trap, but phosphorus pentoxide should be employed as usual to keep water vapour out of the pumping system. A Geryk or a Hyvac mechanical pump may be used to produce the fore vacuum. The pump is illustrated in Fig. 13.

As before the pump is made in two parts, the boiler and the condenser. The boiler is a conical flask of 100 c.c. capacity whose bottom has been drawn in by softening followed by suction. The side limbs for insertion of the sealed-in wires are then prepared. A suitable length of No. 26 nichrome wire is coiled round a glass tube of 4 mm. diameter and is attached to stout tungsten or molybdenum rods of about 1·5 mm. diameter. These will carry the required heating current without introducing undue stresses into the seals. The cleaned nichrome wire is dipped into fused borax, as is the cleaned end of the tungsten or molybdenum wire, to act as a flux. A bead of silver solder is then made to run over the prepared end of the tungsten or molybdenum wire, the heating being carried out with a fine air-coal-gas flame. The prepared end of the nichrome wire is similarly wetted with silver solder and the two ends are brought together in the flame. Very good joints may be made by this means. The excess of fused borax is carefully washed away with water before the sealing wires are cleaned in preparation for sheathing with the sealing glass. Assuming that the pump is made of Pyrex or Hysil glass, a tungsten wire should be sheathed and beaded with G.E.C.W1 or some similar glass and a molybdenum wire should be sheathed and beaded with Kodial.

The nichrome coil is then placed in the flask and the sealing wires are manœuvred into position in the side limbs. Each is heated in turn and is manipulated until satisfactory joints are made. Kodial should be carefully annealed by heating to about 540° C. for ten or fifteen minutes, preferably in a gas muffle, followed by slow cooling to about 400° C., after which the cooling may be somewhat faster. For W1 glass the annealing temperature should be 560° C. When annealed the seals should not be carelessly subjected to temperatures of this order again. If a strain-viewer is available, it may be worth while to see whether the sealing process has introduced undue strain and, if so, to attempt to reduce it by re-annealing.

The construction of the water jacket is less difficult than may appear. The inner tube is prepared and should be sealed at one end with the addition of a wider tube from which the bulb is blown later. The water connection should be added at this stage. Note that a small protuberance should be made on the inner tube at the point where the side tube is to be sealed on.

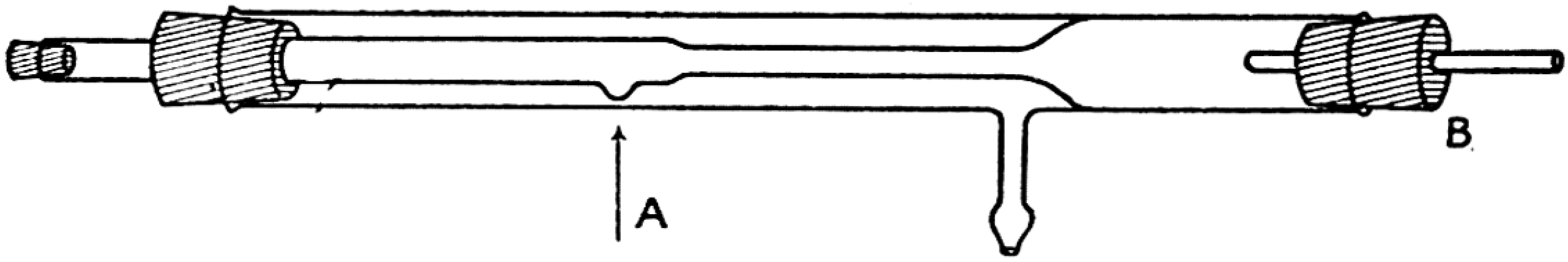


Fig. 14. An early stage in the construction of the sealed in water condenser for a 2-jet oil diffusion pump.

A fine pointed oxy-coal-gas flame is directed as shown by the arrow at A until the two thicknesses of glass are softened. The glass is blown out by a puff through the tube B and the ragged glass is removed by a stroke with a file. B is immediately closed with a cap. A 6-inch length of 6 mm. tubing is then sealed on at A, being blown to shape both through the side tube itself and through the water connection. The whole tube in the neighbourhood of the joint is reheated until the colour of sodium appears in the flame, when it is allowed to cool slowly in a soft bunsen flame. The other end of the water jacket is then sealed, the water exit tube is added and a bulb is blown for admission of the jet system and to take the wide tube for connecting to the apparatus to be evacuated. When this work has been annealed the other end of the condenser may have its bulb completed, with fore pump tube and oil return tube, (Fig. 15).

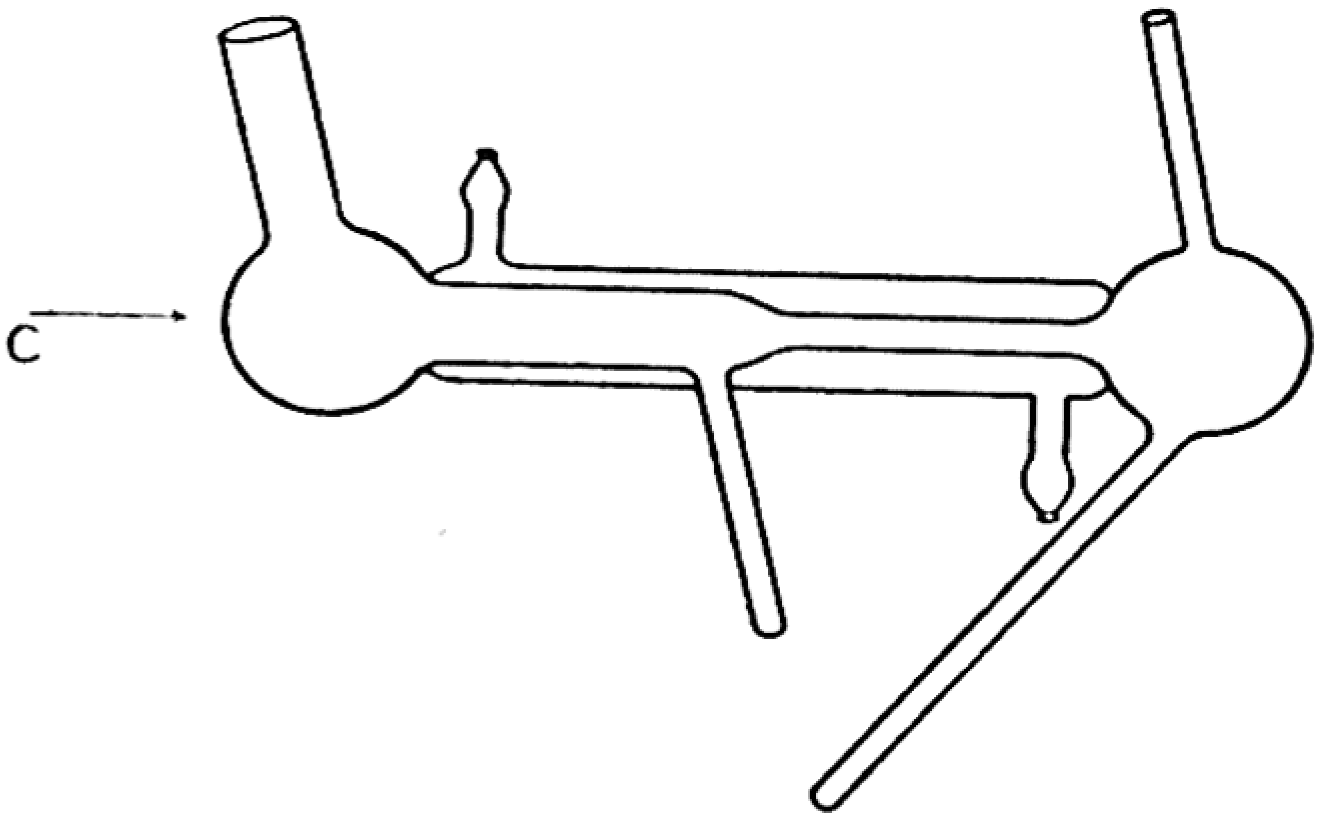


Fig. 15. When the water condenser has reached the stage shown, the jet system is sealed in at a hole blown at C.

The length of the jet system is carefully adjusted so that its end will just enter the throat of the inner tube. A hole of the right size to accommodate the jet system, which has been previously attached to the boiler, is made at C and the seal is completed. The vapour tube from the boiler is then bent to give the pump its final form, the last joins being made in the return tubes.

Acids cannot be used for cleaning this pump without harming the immersion heater, but it may be washed out several times with distilled water, heated to 100° C. in an air oven and dried with a current of dry air. The lagging is then put on the boiler and uptake tube, and enough silicone oil is added to cover the immersion heater. When the required connections have been made the pump is ready for use.

The heating current may of course be alternating or direct. An estimate of the resistance of the nichrome coil is made and a protective resistance is arranged so that, in the first instance, a current of not more than 3 or 4 amps. can be passed. Experience will soon show what external resistance is required to make the pump work smoothly. Air should never be admitted through the fore vacuum side while the oil is hot, as its vapour will be carried into the high vacuum system.

### (5) THE McLEOD GAUGE

It is instructive to connect a McLeod gauge to a mercury diffusion pump and to measure the best vacuum that the pump will give. Of course, the McLeod gauge does not record the presence of condensible vapours, such as mercury, water vapour or hydrocarbons from tap grease or waxed joints, but the degree of exhaustion of the permanent gases that can be produced by the pump is of some interest and the condensible vapours can be excluded to a very large extent, except for mercury. It is better not to connect a McLeod gauge to a system including an oil diffusion pump unless a liquid air trap is used, as the system will become contaminated with mercury and the ultimate vacuum may be spoiled.

A rubberless pattern of McLeod gauge is much to be preferred, as the passage of mercury through rubber contaminates the mercury sooner or later, possibly with mercury sulphide, and it is not desirable to have to clean the gauge very often. The short form of gauge is convenient and is easily made from Pyrex glass. For demonstration purposes it will be unnecessary to measure very low pressures and, in order to avoid sticking of the mercury in the capillary of the gauge, it is better not to choose too fine a capillary tube. If the volume of the capillary is about 0·01 c.c. per cm. of tube a gauge of convenient dimensions can be constructed which will register pressures from about 0·2 down to 0·0005 mm. of mercury. The Pyrex capillary tube selected should be of diameter about 1·1 mm., so that a thread of mercury 5 cm. long will weigh about 0·7 gm. It may be taken that the bore is substantially uniform if there is no appreciable alteration in the length of this thread of mercury over the 40 cm. or so of tubing required. The dimensions are given in Fig. 16.

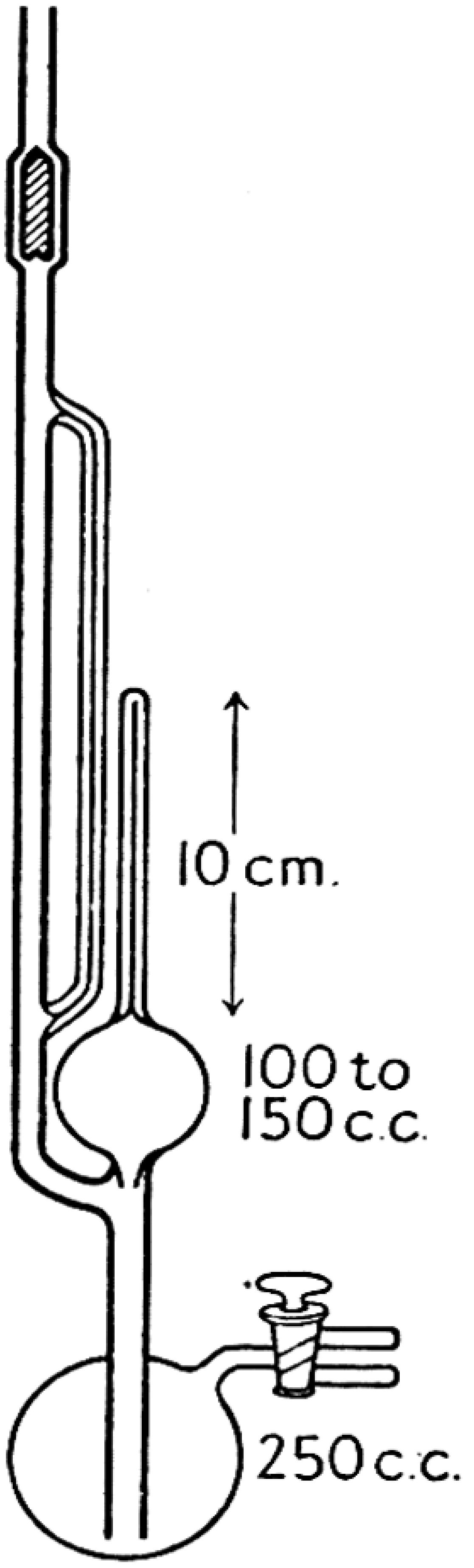


FIG. 16. Short form of all-glass McLeod gauge to measure pressures of about 0·2 to 0·0005 mm. of mercury.

A two-way Pyrex tap will be required and it will be wise, if the apparatus is to be handled by students, to include a glass valve of the pattern shown in the tube connecting the gauge to the vacuum system in order to prevent accidental loss when the mercury is raised by admission of air to the reservoir. The volume of the bulb and capillary to the cut-off point must be determined before joining them to the reservoir. A gauge made according to these instructions gave results as follows :

| | | |
|---|---|---|
| | Volume of bulb and capillary | 136 c.c. |
| | Volume of 1 cm. of capillary | 0·0111 c.c. |
| | Length of air column in capillary | 1·30 cm. |
| | Difference in height of mercury | 0·80 cm. |
| ∴ | Volume of air at 8 mm. pressure | 0·0144 c.c. |

$$P_1V_1 = P_2V_2$$

Hence

$$P_1 = \frac{8 \times 0{\cdot}0144}{136} \text{ mm. of mercury}$$

$$= 0{\cdot}00085 \text{ mm. of mercury.}$$

It is sometimes asked why the top of the capillary tube is not made flat. Although it is quite easy to do this by sealing a small piece of glass rod into the tube when it is made, it is not necessary to do so, as the normal hemispherical seal approximates to the shape of the meniscus of the mercury. If

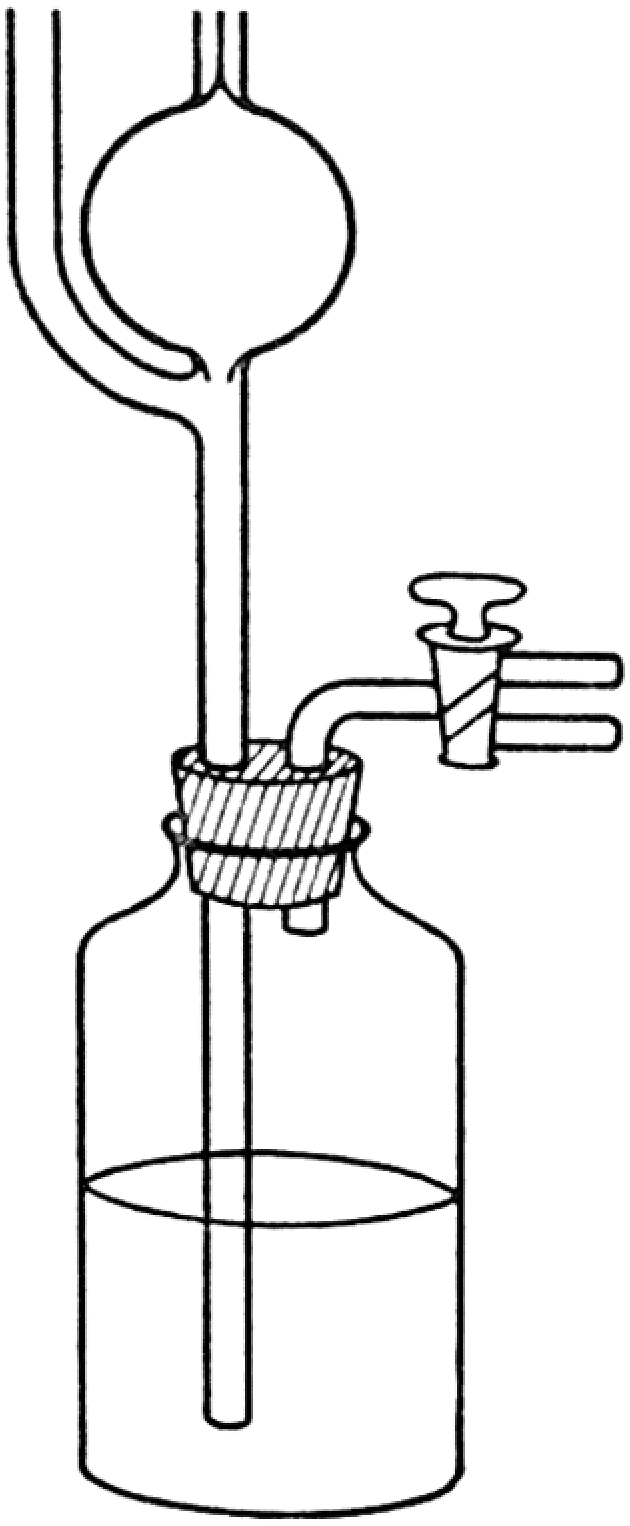


FIG. 17. Simplified form of short McLeod gauge with rubber bung fitted to mercury reservoir.

any difficulty is encountered in sealing the gauge into a glass reservoir, there is no objection to the use of a strong glass bottle fitted with a doubly bored rubber bung, one hole taking the gauge and the other the two-way tap. As there is an air space above the mercury in this reservoir, the mercury will not come into contact with the rubber bung and contamination will not occur. See Fig. 17.

# CHAPTER II

## DEMONSTRATIONS WITH THE DIFFUSION PUMP

### (1) THE DISCHARGE THROUGH AIR, HYDROGEN AND CARBON DIOXIDE

IF a diffusion pump is available a good demonstration can be given to a large audience with a discharge tube about 1 metre long. A hard glass tube of diameter 4 or 5 cm. and length about 1 metre is fitted with electrodes at each end and also with high vacuum taps, as shown in Fig. 19. The design of tap shown is very efficient and, if greased with a good vacuum tap grease, will allow a pressure of $10^{-4}$ mm. to be maintained while the pump is working. The tube is first filled with air and the phenomena of the discharge are demonstrated. By the use of the tap A it is possible to hold a particular state of the discharge while pointing out its details to the audience. The tube is then evacuated until no discharge will pass and tap A is closed. The tap B, which is in communication through

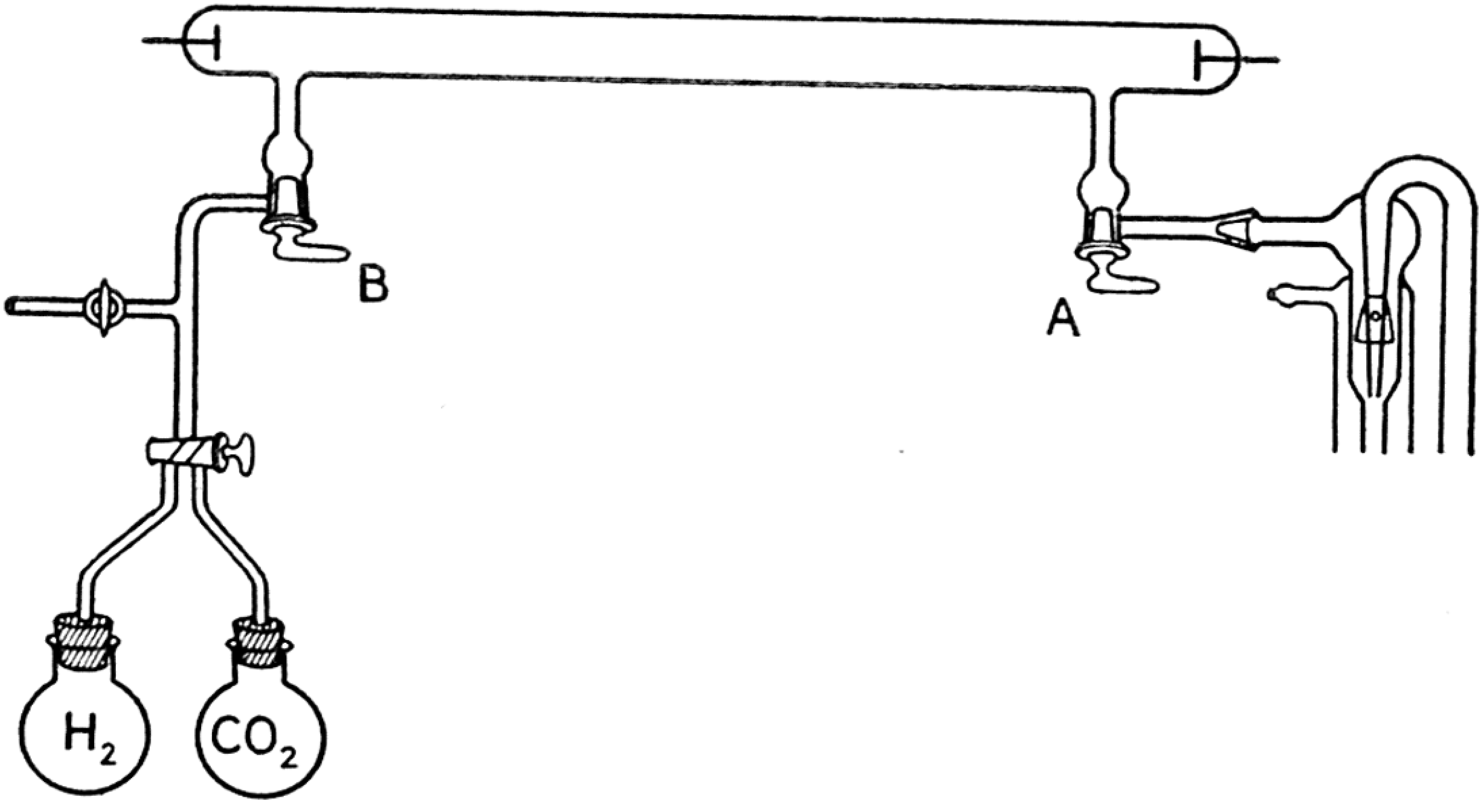


FIG. 18. Arrangement of stopcocks for showing the discharge through three gases in succession.

a good quality 3-way stopcock with two flasks, one filled with dry hydrogen and the other with dry carbon dioxide, is cautiously opened to remove the air from the connecting tube. One of the gases is then admitted to the discharge tube and the characteristic appearance of the discharge may be compared with that obtained in air. The system is then again evacuated up to the 3-way tap and the second gas is admitted.

### (2) THE PERMEABILITY OF PALLADIUM TO HYDROGEN

The passage of hydrogen through heated palladium can readily be shown if a diffusion pump is available. A gas discharge tube of the conventional pattern is constructed, one end having a side tube for connection to a cone and socket joint and the other for connection to a high vacuum tap. A palladium tube, ready for sealing to glass, can be purchased from Messrs. Johnson Matthey & Co. Ltd. for about £2. It is sealed at one end with gold solder and at the other end is connected, also with gold solder, to a short length of platinum tube, so that it can readily be sealed to soda or lead glass. A cone and socket joint sealed with vacuum wax serves to join the palladium tube to the discharge tube thus :

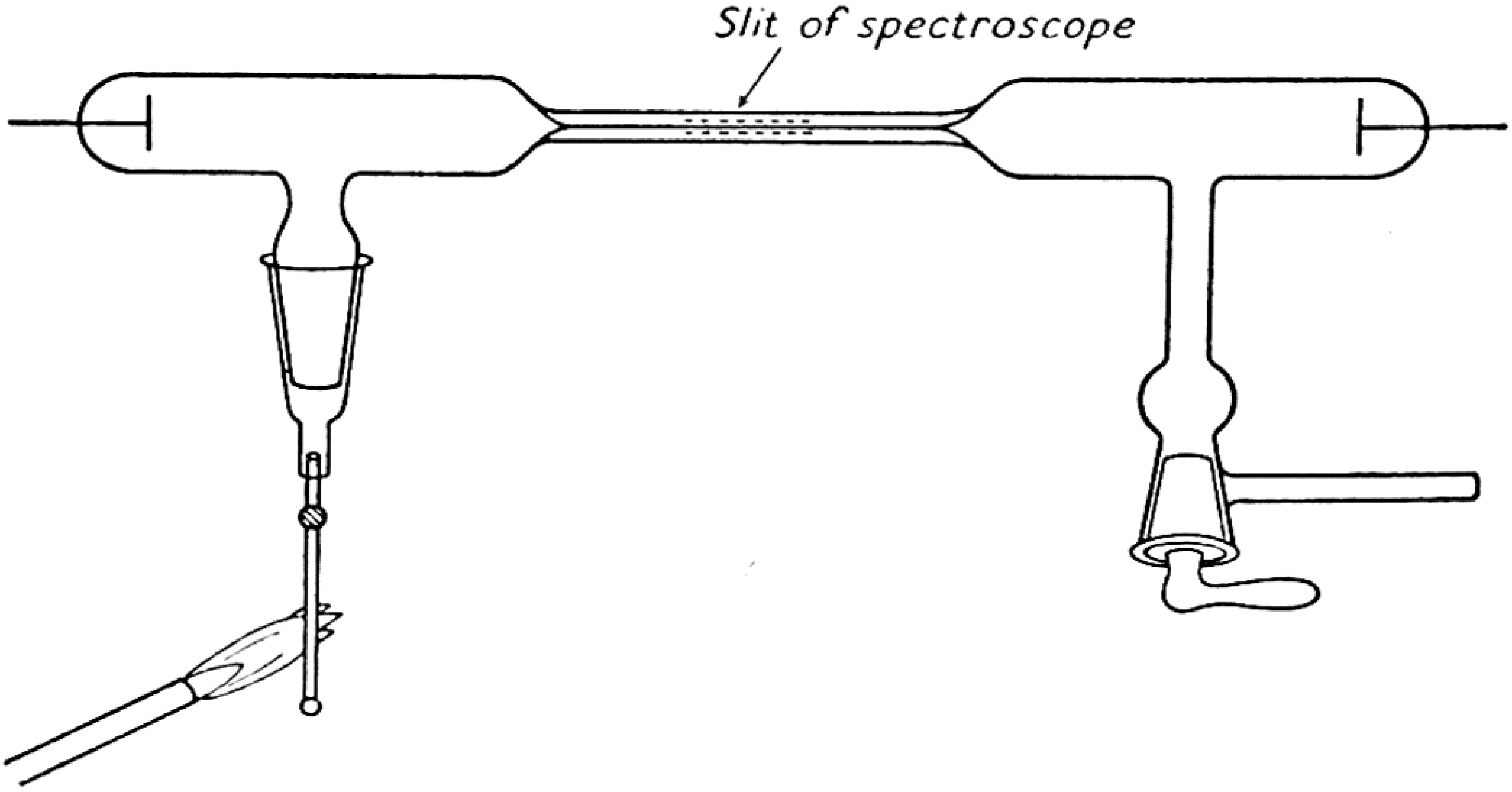


FIG. 19. Arrangement for showing the passage of hydrogen through heated palladium.

The discharge tube is evacuated as completely as possible. This will take some time as the relatively narrow tubing of the tap and the narrow capillary of the discharge tube greatly reduce the speed of the pump. When no discharge will pass the palladium tube is cautiously heated with a small gas flame to a temperature just short of redness, and if the induction coil is kept running, the bright red discharge of hydrogen soon makes its appearance in the capillary. The presence of hydrogen should be confirmed by means of a spectroscope, the characteristic lines being compared with those obtained from a known source.

### (3) THERMIONIC EMISSION

Thermionic emission may also be qualitatively investigated. A demountable discharge tube is prepared, having a good quality stopcock attached to the side tube for admitting air, in order to expedite the replacement of the filament assembly. Two of these are prepared, with interchangeable ground

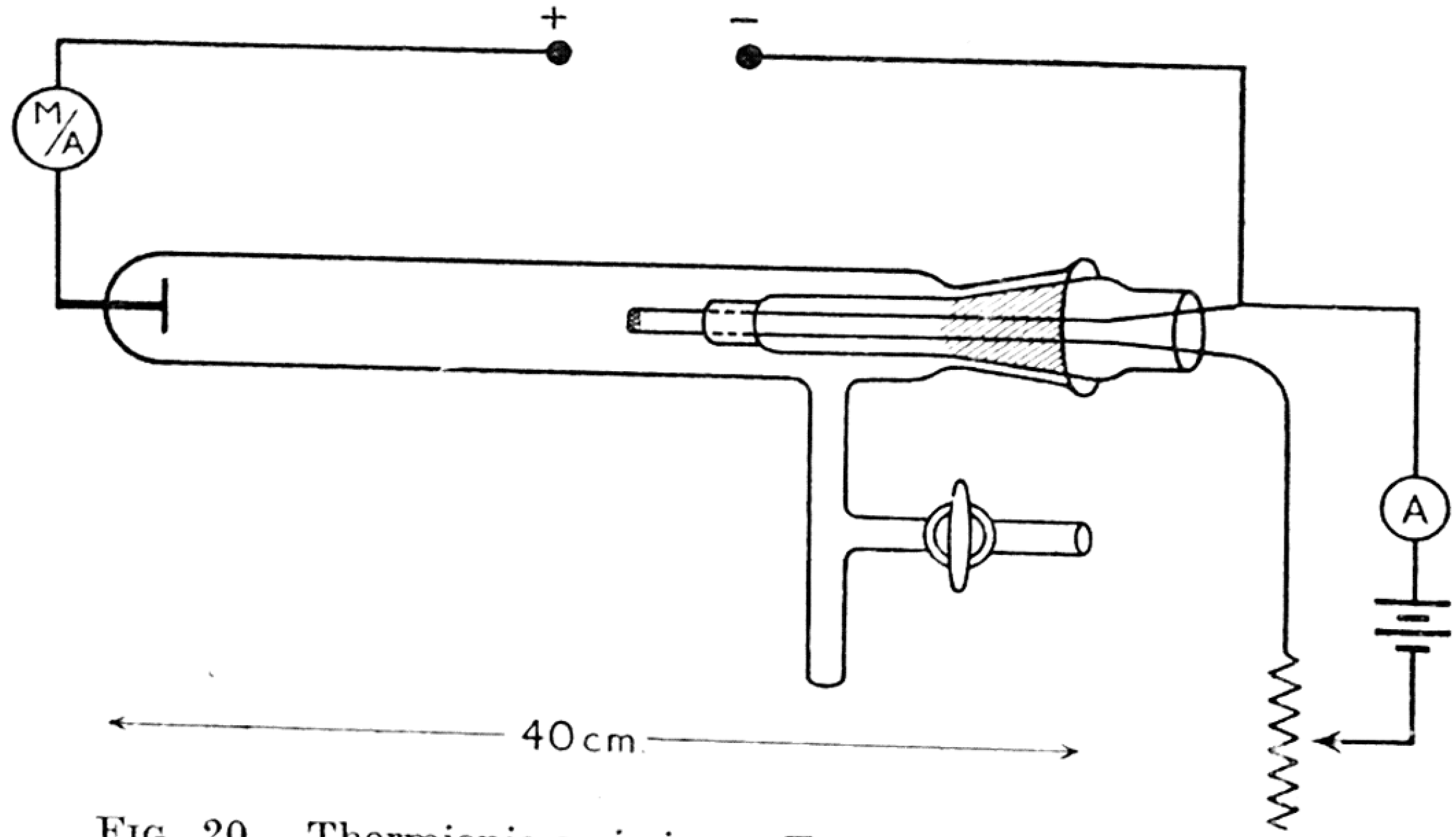


FIG. 20. Thermionic emission. Two filaments are prepared with their supporting seals and ground conical joints. The ion current is indicated by a milliameter in the coil circuit.

conical joints to fit the discharge tube. Recommended dimensions are given in Fig. 20.

The discharge tube is of Pyrex glass and has a conical seating at one end in which the two cathode assemblies can be inserted in turn. These should be ground to give an approximate fit, but need not be ground very precisely, as the joints are to be made with one of the vacuum waxes, such as Edwards' W.E.3. The cathode press may be made also of Pyrex or of any hard glass through which the worker can seal metal wires. Molybdenum seals well if sheathed in Kodial, particularly into Monax. Alternatively the press may be made entirely of Kodial, but this glass is expensive. To save molybdenum, the wires are joined by silver solder to 22 gauge copper wires where they emerge from the glass. The joint is made by means of a flux of fused borax. A small tray with upturned edges is made of platinum foil and some borax is fused in it in the blowpipe flame. The ends of the cleaned molybdenum and copper wires are then heated and dipped in the fused borax until a uniform layer of the flux covers about 1 cm. of the end of each. A small piece of silver solder is then taken up on the molybdenum wire and is heated in a fine-pointed blowpipe flame until the solder has run and has wetted 5 mm. or so of the end of the wire. The end of the copper wire with the borax on it is then heated and is brought into contact with the fused solder on the molybdenum wire. The solder will harden as soon as it is removed from the flame. The two wires may be held in pin vices or otherwise. The excess flux is removed by washing with water.

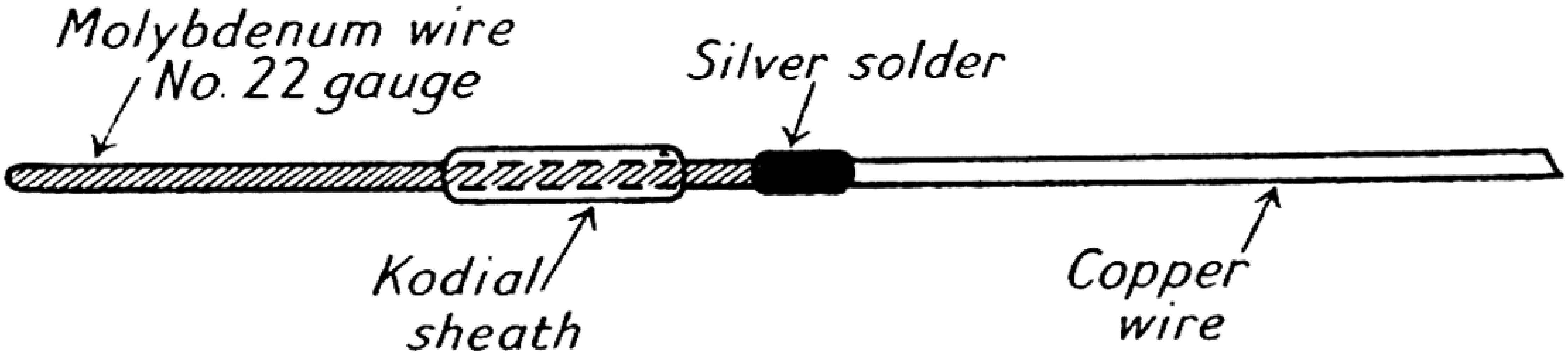


FIG. 21. Method of preparing molybdenum wire for sealing to glass.

When this joint has been made the molybdenum wire must be cleaned as described below before any attempt is made to seal it into glass. A small hard glass test-tube is filled with solid potassium nitrite and is held sloping at about 60° to the horizontal. The potassium nitrite is then just fused and the molybdenum wire is dipped in the fused salt to a depth of about 5 cm. and is held there for about five seconds. It is then withdrawn, washed with tap water and with distilled water, and allowed to dry in air. It should not be touched with the fingers, as it is to receive a sheath of Kodial glass along about 2 cm. of its length. A piece of Kodial tubing is drawn down so that it just slips over the molybdenum wire. Lengths of about 1·5 cm. are cut off. The molybdenum wire is oxidized superficially by heating it in a soft bunsen flame for about five seconds and the glass sheath is slipped into place. The glass is then heated in a fine blowpipe flame, starting at one end and rotating the wire so that the glass sheath is fused uniformly to it with the exclusion of all air. Four of these composite wires should be prepared and sheathed with glass, two being required for each cathode assembly. The easiest way to ensure a trouble-free seal is to use Kodial glass for the tube that is to carry the filament. A piece of 18 or 20 mm. Kodial tubing is blown out to give a thick-walled bulb and is then tapered to make the waxed joint with the main tube. This tapered joint need not be ground very completely, but

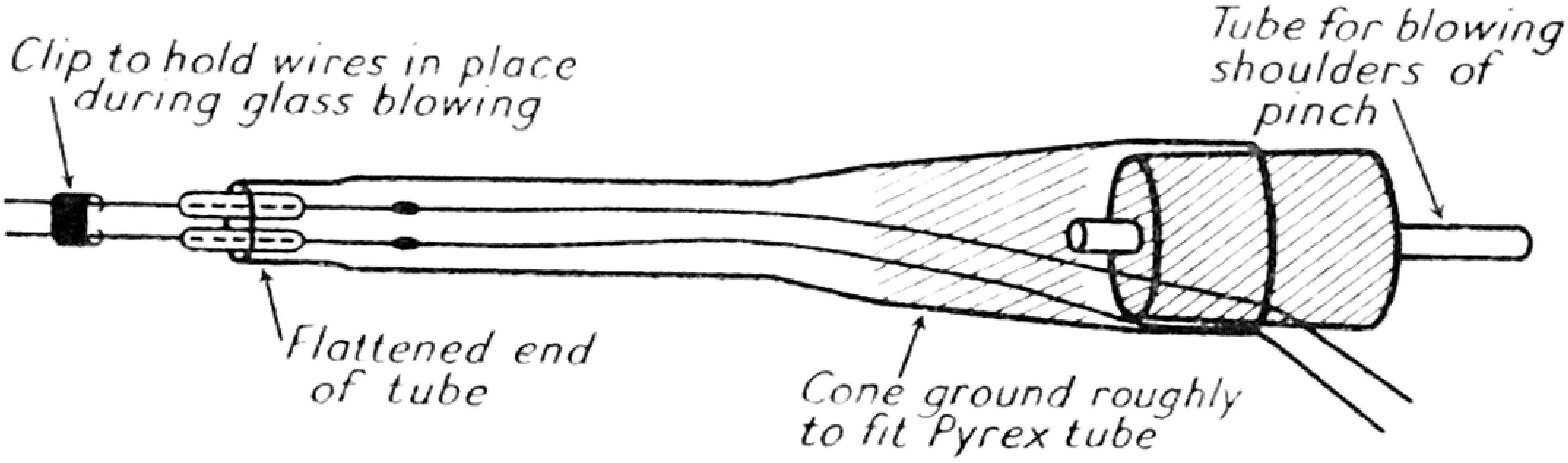

Clip to hold wires in place during glass blowing
Tube for blowing shoulders of pinch
Flattened end of tube
Cone ground roughly to fit Pyrex tube

FIG. 22. To ensure a satisfactory joint the assembly shown should be carefully prepared before the final sealing operation.

partial grinding with carborundum and water is recommended if the filament is to be satisfactorily centred when the tube is finally assembled. The other end of the Kodial tube is flattened to accommodate the two molybdenum wires as illustrated in Fig. 22.

The wires may be held parallel to one another at the correct distance apart by a small brass clip which is pinched into position with pliers. A cork and open tube should be fitted to the other end of the Kodial tube as it will be necessary to blow out the shoulders of the pinch, when the glass has been softened for the purpose of closing the flattened part of the tube round the sheaths of the molybdenum wires. A pair of tongs with small plates of gas carbon attached to their tips may be used for shaping the pinch. When the seal has been satisfactorily completed the tube should be annealed by placing it in an oven at 540° C. for ten minutes, and then allowing a fall of temperature of 2° C. per minute down to 400° C. The source of heat may then be turned off and the glass tube is allowed to cool to room temperature without opening the oven. After this treatment the seal will be found to be free, or nearly free, from strain.

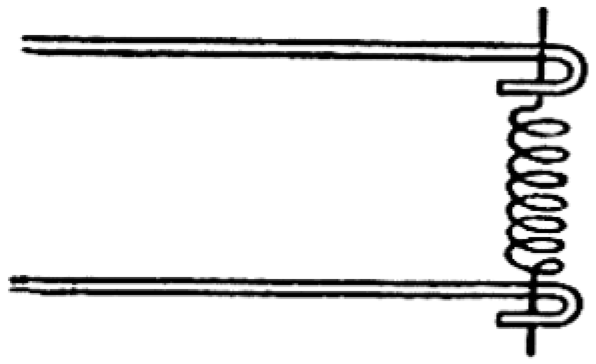


FIG. 23. The tungsten filament is securely held in place by crushing the molybdenum wire hooks with pliers.

The filament consists of ten or twelve turns of 34 or 36 S.W.G. tungsten wire wound on a needle in a close helix. The ends of the molybdenum wires are bent over with fine watchmakers pliers and the tungsten filament is placed in the hooked ends so formed. The molybdenum hooks are then crushed firmly on the tungsten wire and are found to give a satisfactory contact (Fig. 23).

One of these cathode assemblies is warmed and waxed in position in the discharge tube. When the waxed joint is cold, the tube is evacuated until no discharge will pass. A milliammeter is interposed between the induction coil and the discharge tube, on the anode side. It may be insulated by supporting it upon an ebonite or bakelite pillar. No current will flow through the tube when the cathode is cold and readings of the thermionic current through the tube are taken as the filament current is increased. A safe maximum of filament current will be about 3·5 amperes.

The diffusion pump is now stopped and after an interval for cooling, air is cautiously admitted to the discharge tube. The filament assembly is removed. The second filament is painted with a suspension of thorium dioxide in water and, after drying over a flame, it is inserted in the discharge tube. When the filament current is turned on the greatly increased thermionic emission of the thoriated filament is shown by the increased currents through the tube.

# CHAPTER III

## THE MEASUREMENT OF $\frac{e}{m}$ FOR ELECTRONS

BEFORE it was known how to measure separately either the charge or the mass of the individual particles which constitute cathode rays Sir J. J. Thomson had devised and carried out experiments which gave the value of the ratio of charge to mass. In 1897 he used a magnetic field to deflect a stream of cathode rays for a known time into a metal box which was connected to a quadrant electrometer, thus giving the total charge. The total energy of the stream was found by means of a thermo-junction. From his results he calculated the value of the ratio $\frac{e}{m}$, but this method is difficult to carry out with accuracy and is not suitable for an elementary demonstration. Subsequently he used a simpler method which is easily reproduced in the laboratory. A discharge tube with the anode in a side tube gives a cathode stream which falls upon an anti-

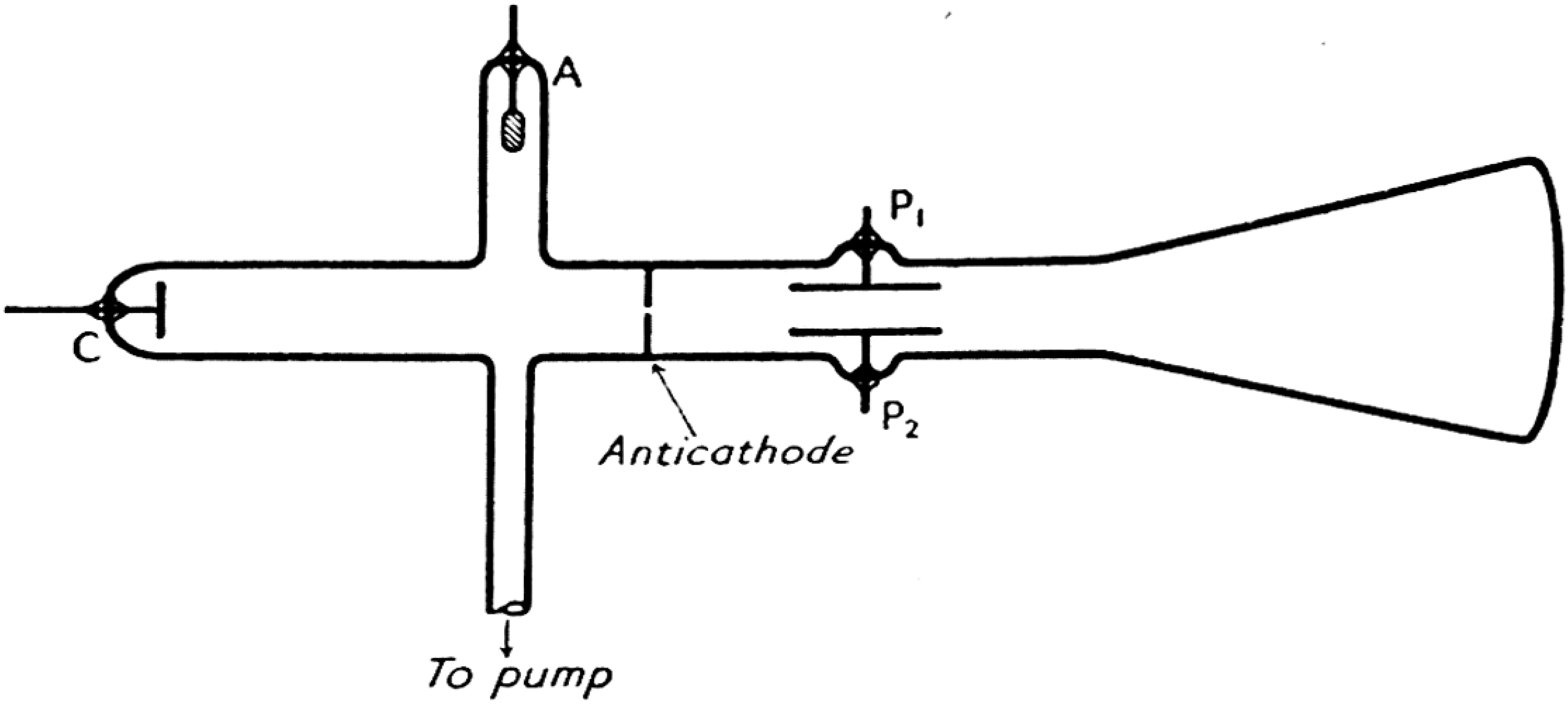


FIG. 24. A discharge tube for determining $\frac{e}{m}$ by electrostatic and magnetic deflections.

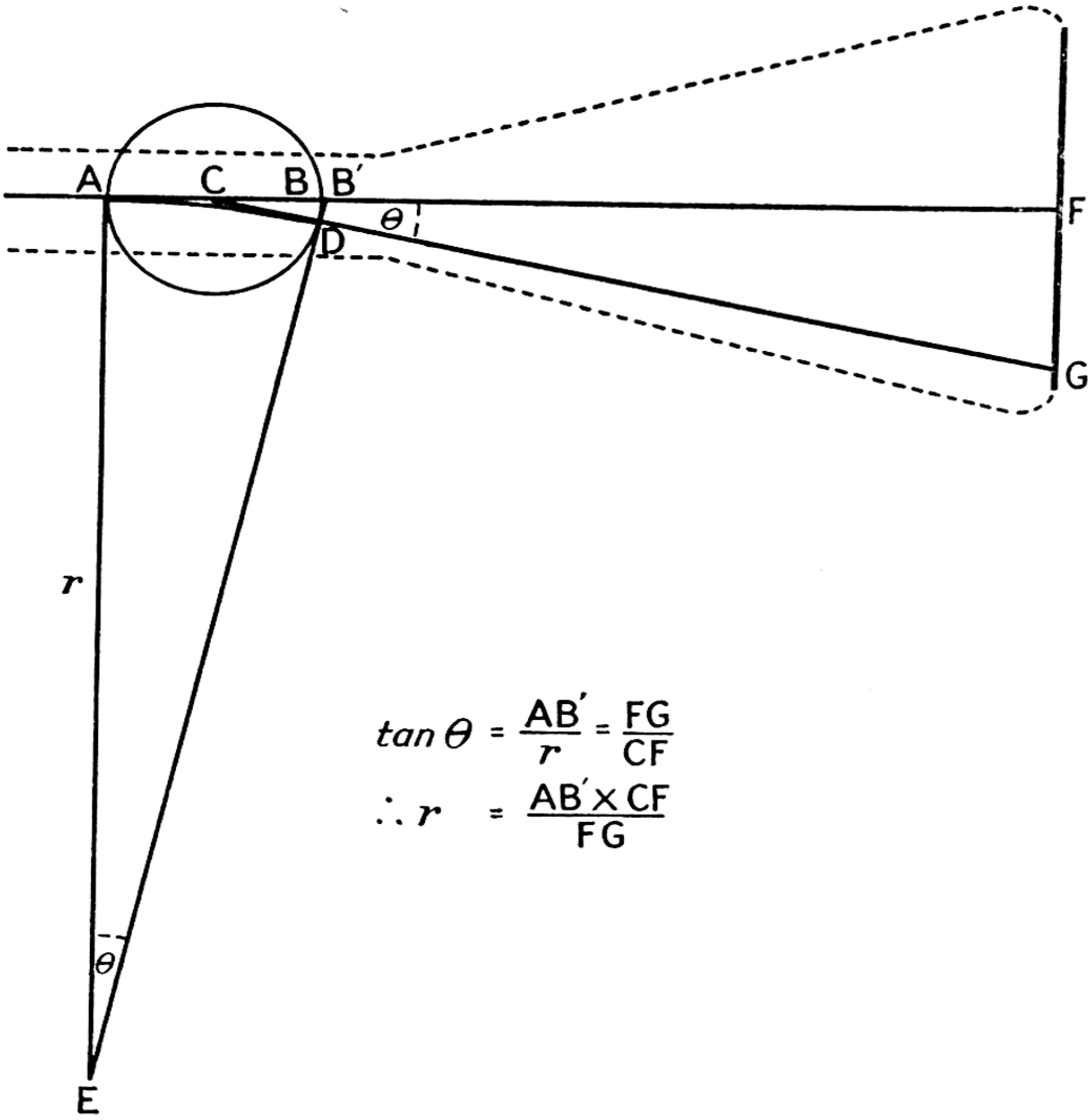
cathode consisting of a metal plate with a small hole in its centre. Most of the charge is collected by this plate and soon leaks away, but a stream of cathode rays passes through the hole, continues between two parallel metal plates which have connections outside the tube, and falls upon a screen of some fluorescent material, or phosphor, thus giving a luminous spot. The tube must be pumped to a pressure of about 0·01 mm. of mercury, say, with a Hyvac or a small diffusion pump, but if too much air is withdrawn no cathode rays are produced.

The determination of $\frac{e}{m}$ is done with this apparatus by means of two separate experiments. In the first, the spot on the screen is deflected upwards or downwards by connecting a source of potential of a few hundred volts to the plates $P_1$ and $P_2$. A magnetic field is now produced perpendicular to the plane of the paper so that its lines of force are perpendicular to those of the electric field between the plates. This is done by means of a solenoid through which the current can be altered until the luminous spot is returned to its original undeflected position. The forces on the cathode stream then balance one another and the velocity of the particles can be found, for a magnetic field of $H$ oersteds produces a force $Hev$ on a particle of charge $e$ which is moving with velocity $v$. The force due to the electric field $E$ on an electron is $Ee$.

Hence
$$Hev = Ee$$
or
$$v = \frac{E}{H}.$$

$E$ is found by converting volts to electromagnetic units of potential and dividing by the distance between the plates $P_1$, $P_2$. $H$ is calculated approximately for a long solenoid from the relation $H = \frac{4\pi nI}{10}$ oersteds, where $n$ is the number of turns per centimetre and $I$ is the current in amperes. The fact that the tube is inserted in a gap in the solenoid may be ignored in view of the approximate nature of the other measurements. $v$ may be about $5 \times 10^9$ cm./sec.

The second experiment consists in measuring the deflection of the spot produced by a known magnetic field. A vertical scale with millimetre divisions may be pasted on the screen end of the cathode ray tube. It can be shown that, instead of traversing a diameter of the solenoid, the particles are deflected upwards or downwards in a circular path. When they emerge from the magnetic field they proceed in a straight line to the screen. If $r$ is the radius of the circle into which they are bent



$$\tan\theta = \frac{AB'}{r} = \frac{FG}{CF}$$

$$\therefore r = \frac{AB' \times CF}{FG}$$

FIG. 25. Scale drawing showing the relations between $r$ and the dimensions of the apparatus.

while traversing the magnetic field, we have $Hev = \frac{mv^2}{r}$, or

$$\frac{e}{m} = \frac{v}{rH}.$$

$v$ and $H$ have already been found. It remains to calculate $r$ from the deflection of the spot.

Let $C$ in Fig. 25 be the centre of the solenoid and let $ABF$ be the path of the undeflected particles. Their actual path is $ADG$, where $AE$ is the radius of the curved part of it. Let the angle $AED$ be called $\theta$. Let $ED$ be produced to $B'$. Then for small values of $\theta$, $B$ and $B'$ nearly coincide. The angle $FCG$ is also $\theta$.

Then
$$\tan\theta = \frac{AB'}{r} = \frac{FG}{CF}$$

and
$$r = \frac{AB' \times CF}{FG}.$$

But $AB'$ is nearly equal to the diameter of the solenoid and $CF$ is the distance of the fluorescent screen from the centre of the solenoid. Hence a numerical value for $r$ can be inserted in the equation $\frac{e}{m} = \frac{v}{rH}$.

The tube may conveniently be made in two parts, one carrying the electrodes and the other the screen. A length of 25–30 mm. bore hard-glass tubing is taken and closed at one end. Side tubes are sealed on 8 or 9 cm. from the closed end to accommodate the anode and the connection to the pump. Eight centimetres away from these tubes protuberances are made in which the plates for the electrostatic field are to be sealed. The cathode, which is a flat aluminium plate, is sealed in first, then the anode, which may be of any convenient size and shape. The anticathode is a disc of aluminium or nickel sheet with a hole of 1·5 mm. diameter in the centre. It may be held in place by softening the glass at its edges and making indentations to prevent movement. There need be no external connection. The electrostatic plates may be of aluminium or nickel, but should be of the same size, say 4 cm. × 1·3 cm., and must be as nearly parallel to one another and to the axis of the tube as possible. The tube is cut off square about 3 cm. beyond the plates for joining to the conical flask which contains the fluorescent screen.

The fluorescent screen may be obtained from the tube of a cathode ray oscillograph, or a burned-out television tube, but screens can be made in the laboratory without very much difficulty if desired. Luminescent materials or phosphors should be purchased, as they are difficult to make on a small scale. Activated zinc silicate gives a green fluorescence. Cadmium tungstate gives a blue colour, but on account of its high density it is rather more difficult to spread in a uniform layer. A conical Pyrex flask of 500 c.c. capacity is taken and the flat bottom is softened in a large oxygen-coal-gas flame so that the end can be blown out slightly to give a convex surface. The phosphor may be applied by settling through a liquid, by spraying a suspension of it in some volatile solvent, or by dusting. The operations of settling and pouring off the clear liquid require care and take some time, but can be made to give screens of uniform density. Some television screens are made by this process. The most convenient method is perhaps by spraying, a suspension of the phosphor in acetone being used. A small amount of boric acid may be used as a binder. After heating the screen to a temperature of 350°–400° C., to remove all trace of the suspending liquid, it will be found that the phosphor is quite firmly attached to the glass surface.

The completed tube is connected to the pump and is exhausted until a bright spot appears on the screen when the potential difference from a small induction coil is applied. The electrostatic plates are connected to a 120-volt dry battery, or 240 volts may be used if the deflection given by 120 volts is too small. The solenoid consists of a cardboard tube closely wound with a single layer of No. 28 d.c.c. copper wire for a length of 30 cm. or so. The diameter of the tube may be about 8 cm. When wound, the tube is cut in two, so that the cathode ray tube can be placed between the two halves. Two or three accumulators, a 0–500 milliammeter and a sliding resistance of a few hundred ohms will give the required control of the magnetic field. The electrostatic field is now applied and the spot is returned to its undeflected position by adjustment of the magnetic field. The current required to produce this field is noted. The electrostatic field is then switched off, the same magnetic field as before is applied and the distance through which the spot has been moved is read off the paper scale on the screen. If the dimensions of the tube and the number of turns of wire per cm. of the solenoid are known, an approximate value of the ratio $\frac{e}{m}$ for electrons can now be calculated.

The author's tube has electrostatic plates which are 3·8 cm. long and 1·5 cm. apart. The front edge of the plates is 20·4 cm. from the screen. The solenoid has fourteen turns per cm. and is 8·7 cm. in diameter.

In a particular experiment the potential difference applied to the plates was 120 volts, whence

$$E = \frac{120 \times 10^8}{1{\cdot}5} \text{ e.m.u./cm.}$$

and the current through the solenoid was 0·085 amp.

$$H = \frac{4\pi n I}{10} \text{ oersteds (approx.)}$$

$$\therefore \qquad H = \frac{4\pi \times 14 \times 0{\cdot}085}{10} = 1{\cdot}5 \text{ oersteds.}$$

$$Hev = Ee$$

$$v = \frac{E}{H}$$

Hence

$$v = \frac{120 \times 10^8}{1{\cdot}5 \times 1{\cdot}5}$$

$$= 5{\cdot}3 \times 10^9 \text{ cm./sec.}$$

The radius of the deflected beam is the product of the diameter of the solenoid and the distance of its centre from the screen divided by the linear deflection of the spot. This was 0·9 cm.

Hence $$r = \frac{8{\cdot}7 \times 22{\cdot}3}{0{\cdot}9} \text{ cm.}$$

But $$Hev = \frac{mv^2}{r}$$

and $$\frac{e}{m} = \frac{v}{rH}$$

$$\therefore \quad \frac{e}{m} = \frac{5{\cdot}3 \times 10^9 \times 0{\cdot}9}{8{\cdot}7 \times 22{\cdot}3 \times 1{\cdot}5}$$
$$= 1{\cdot}64 \times 10^7 \text{ e.m.u./gm.}$$

This answer is of the correct order. The accepted value is $1{\cdot}759 \times 10^7$ e.m.u./gm.

A commercial cathode ray tube can be used for measuring $\frac{e}{m}$, if it is not convenient to make one in the laboratory. According to J. B. Hoag, the author of *Electron and Nuclear Physics*, forty-three modifications of systems employing cathode ray apparatus have been devised from which the ratio $\frac{e}{m}$ may be determined.

# CHAPTER IV

# POSITIVE RAY PARABOLAS AND THE MEASUREMENT OF $\frac{e'}{m'}$ FOR PROTONS

J. J. Thomson's deflection of a stream of positive ions by means of coincident electric and magnetic fields marked an epoch in chemical knowledge, in that his work led to the development of the mass spectrograph and thence to the physical corroboration of the values for the atomic weights which had already been adopted by chemists. His experiment is thus of fundamental importance and ought to be repeated and shown to students if it can be done without undue difficulty. For the measurements of the deflections to be of any significance, the apparatus must be designed so that the electric and magnetic fields are fairly uniform in the region through which the positive ions are passing. The system adopted is to establish the electric field between the poles of an electro-magnet, the pole pieces being insulated from one another by a thin layer of some suitable substance such as mica or red fibre, which will not materially diminish the magnetic flux. This part of the apparatus is integral with the cathode and must be made with some precision :

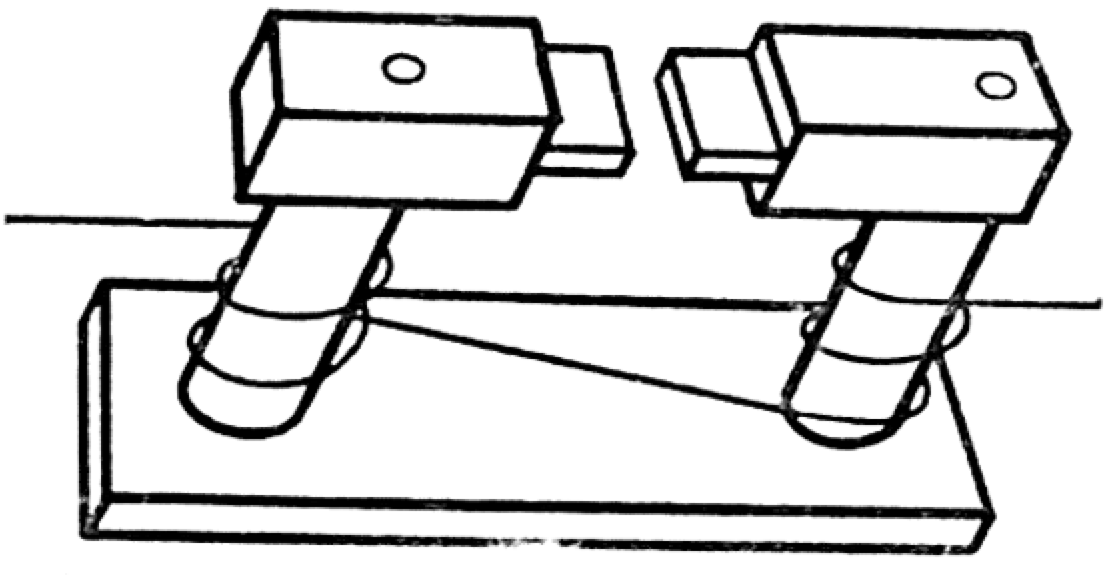


Fig. 26. Specially constructed electromagnet with pole-pieces insulated from the core and from the cylinder which carries the perforated cathode.

The pole pieces are fitted into a thick brass cylinder which is soldered to the cathode at one end and at the other end is grooved or shaped to carry the fluorescent screen. A 1-inch brass tube is soldered between the slots into which the magnet poles fit for connection to the diffusion pump. This tube may have a flange which is carefully ground flat for the attachment of a glass tube by means of vacuum grease or soft wax.

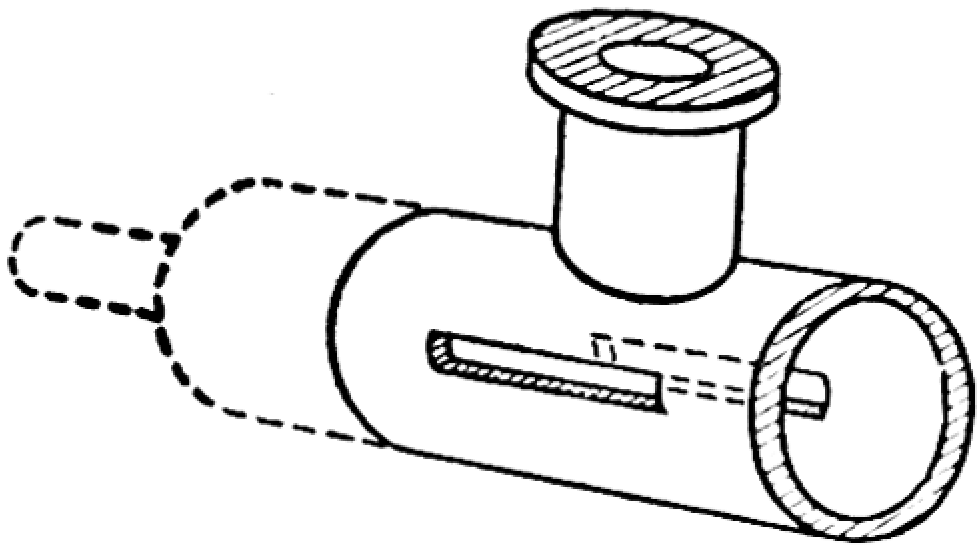


FIG. 27. Brass tube with slots into which the insulated pole pieces fit.

The cathode is drilled axially with a hole 1–1·5 mm. in diameter and is about 5 or 6 cm. long. A channel is drilled in the cathode block for the admission of gas, or alternatively a side tube may be attached to the discharge tube. The cathode is cooled by means of a coil of brass or copper tubing through which cold water flows, thus preventing the wax of the joints from melting when the tube is in use. The discharge tube is of Pyrex glass. It is about 50 cm. long and is 4 or 5 cm. in diameter. The anode is a molybdenum disc which has been firmly hammered to a stout molybdenum wire of diameter 1·5 or 2 mm. The wire is cleaned by dipping it in molten potassium nitrite, washed with water, dried and sheathed with Kodial glass. A Phœnix bead is then added and the anode is sealed into the discharge tube, care being taken that there are no re-entrants in the neighbourhood of the seal and that the strain imposed on the glass by the sealing process is relieved by annealing. The discharge tube is waxed to the cathode cylinder by inserting it in a groove cut specially to accommodate the size of glass selected.

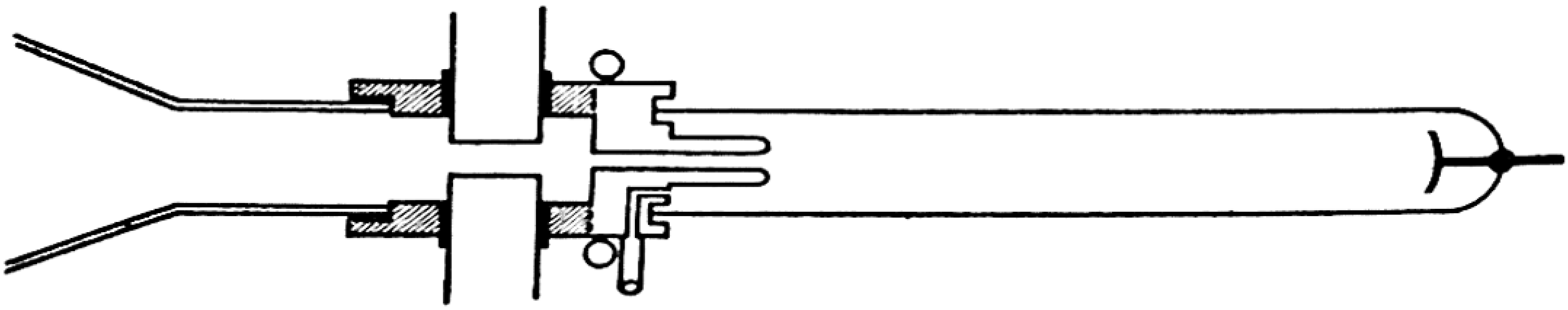


FIG. 28. Axial section of apparatus showing entry for hydrogen and section of cooling coil.

Further details of a slightly more elaborate apparatus of this kind are given in *Electron and Nuclear Physics*, by J. B. Hoag, published in this country by Messrs. Chapman and Hall.

Provision is required for the introduction of a gas, or gases, into the discharge tube. If the operator is content to use hydrogen, a palladium tube may be fitted to the channel provided in the cathode or to a side tube in the main discharge tube. The apparatus becomes much more useful if a needle valve is fitted, together with reservoirs for gases. A very good valve is supplied by Messrs. Edwards & Co. Ltd., but the cost is considerable. The valve may be attached to the gas reservoir as shown :

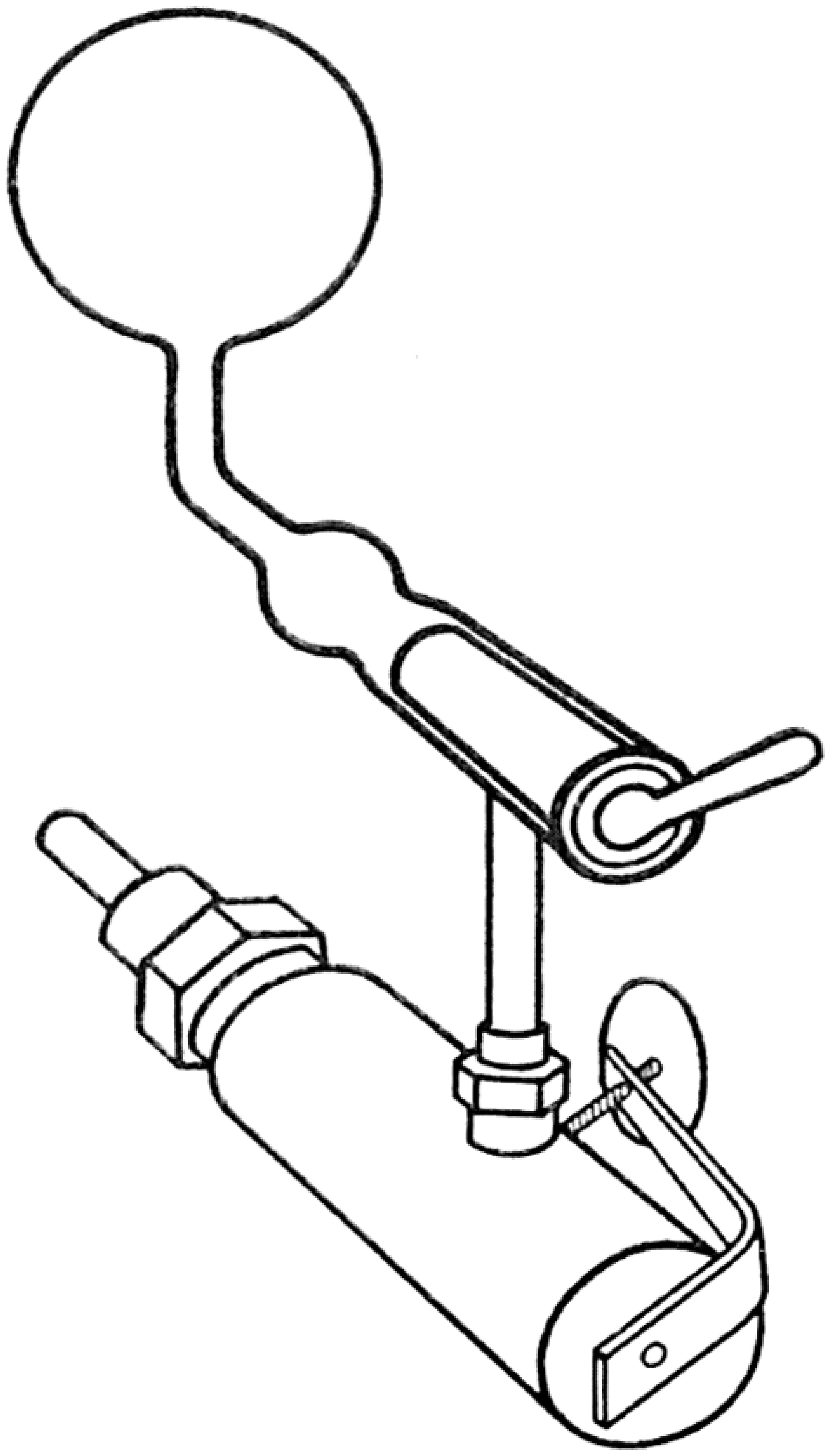


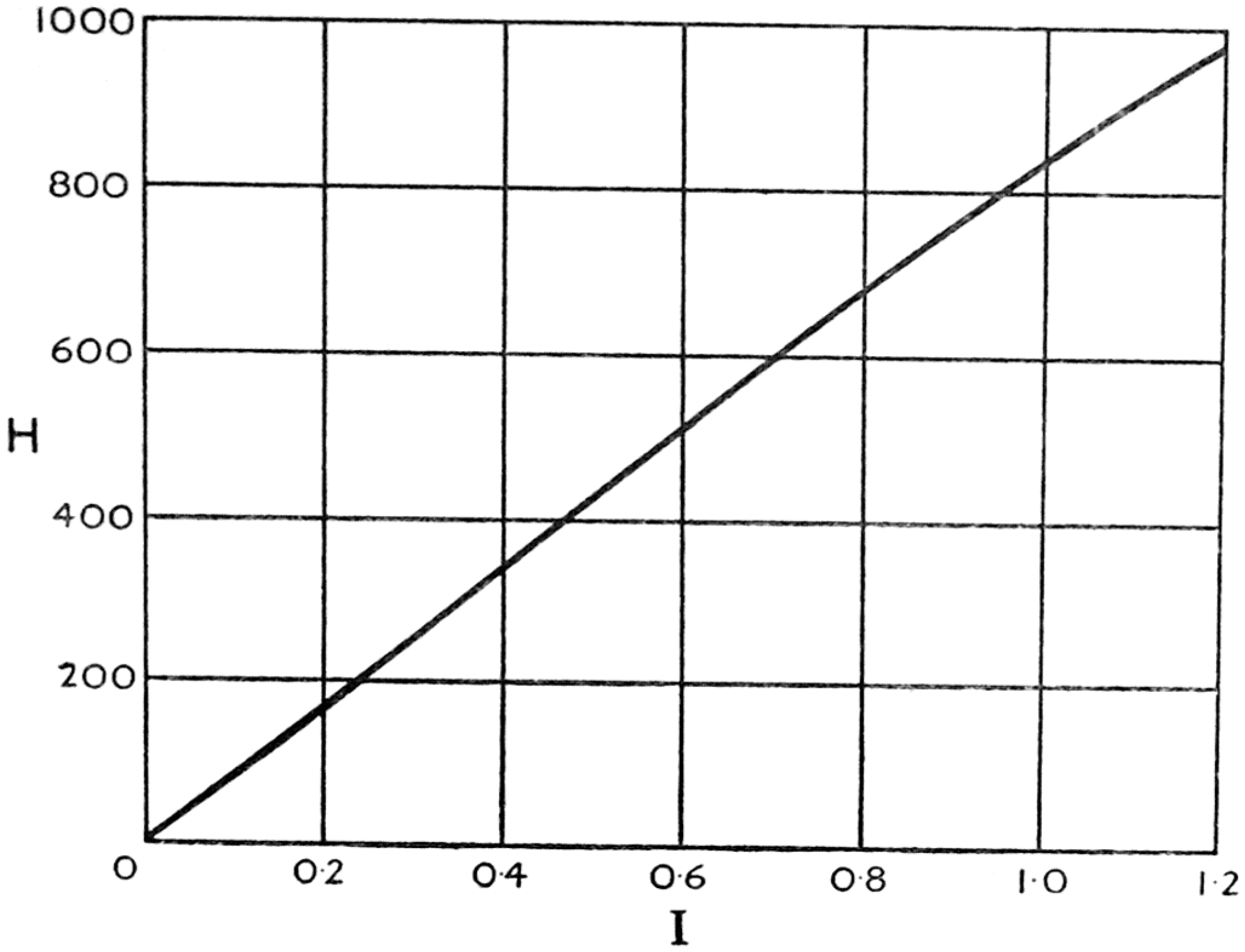
FIG. 29. Arrangement of bulb containing hydrogen fitted to needle valve.

A small spherical bulb of 50 or 100 c.c. capacity is attached to a high vacuum tap, the second tube from the tap being waxed to the brass union connection of the needle valve. The bulb and tap are disconnected, evacuated and filled with the gas to be introduced into the apparatus. The needle valve will be found to give very good control of the rate of entry of gas into the discharge tube.

The method of making fluorescent screens has already been given (p. 40). If any difficulty should arise the bulb and screen of a cathode ray oscillograph or a television tube serves very well.

When the apparatus has been completed it is joined by a short wide tube to an oil diffusion pump backed by a good mechanical pump. A phosphorus pentoxide tube is inserted between the two pumps and evacuation is started. A new tube system often continues to give off gas for some time when first exhausted, especially a composite apparatus of this kind which cannot be outgassed by heating, as it has several waxed joints. It should be pumped for an hour or two and, if possible, left overnight under vacuum to allow the phosphorus pentoxide to clean up any water vapour that may be present. It will be found that the narrow cathode canal slows down the pumping very considerably, but it is necessary to ensure that the pressure in the discharge tube can be reduced to about 0·001 mm. of mercury, when it will be found that no discharge will pass from a small coil.

In order to work the apparatus about 50 Kv. or more are necessary. A large coil giving at least a 4-inch spark or an X-ray transformer should be used. The electric field is obtained by connecting the insulated pole pieces to two 120-volt dry batteries in series, a voltmeter of established accuracy giving the voltage across the plates. The current through the field windings of the magnetic circuit is controlled by a rheostat and must be carefully measured, as it will be necessary to establish the value of the magnetic field given by different currents in a subsequent experiment. This is done by the use of a search coil and a ballistic galvanometer, a calibration curve for the apparatus being plotted to show field strengths against currents through the magnet windings. A typical curve is shown below :



| I *in amperes* | 0·2 | 0·4 | 0·6 | 0·8 | 1·0 | 1·2 |
|---|---|---|---|---|---|---|
| H *in oersteds* | 170 | 340 | 510 | 680 | 840 | 990 |

FIG. 30. Calibration curve showing the value of the magnetic field between the pole pieces with different currents through the field windings of the electro-magnet.

When an X-ray vacuum has been established in the discharge tube a little hydrogen is allowed to enter and, the pumps still working, the accelerating voltage is applied. The cathode must be efficiently earthed. The anode end of the tube is dangerous while working and must be avoided. A central spot is produced on the screen which is deflected up or down by the magnetic field and to right or left by the electric field. If all the positive ions had the same velocity the effect of establishing both fields simultaneously would be to deflect the spot to a point in the quadrant between the directions of the separate deflections, but because the beam of positive ions consists of particles of different velocities, the deflected spot is drawn out into a parabola (see Plate I, C). By reversing the magnetic field or the electric field, or both together, the parabola can be moved into each of the quadrants of the screen in turn, but it always has the same shape. The co-ordinates of any point on it can be read off by pressing a piece of transparent cellophane which has been ruled, say, in 1 cm. or 0·5 cm. squares over the end of the fluorescent screen. The recording of these values of the co-ordinates for particular values of the electric and magnetic fields is the purpose of the experiment and from them the value of $\frac{e'}{m'}$ for the ions used can be calculated.

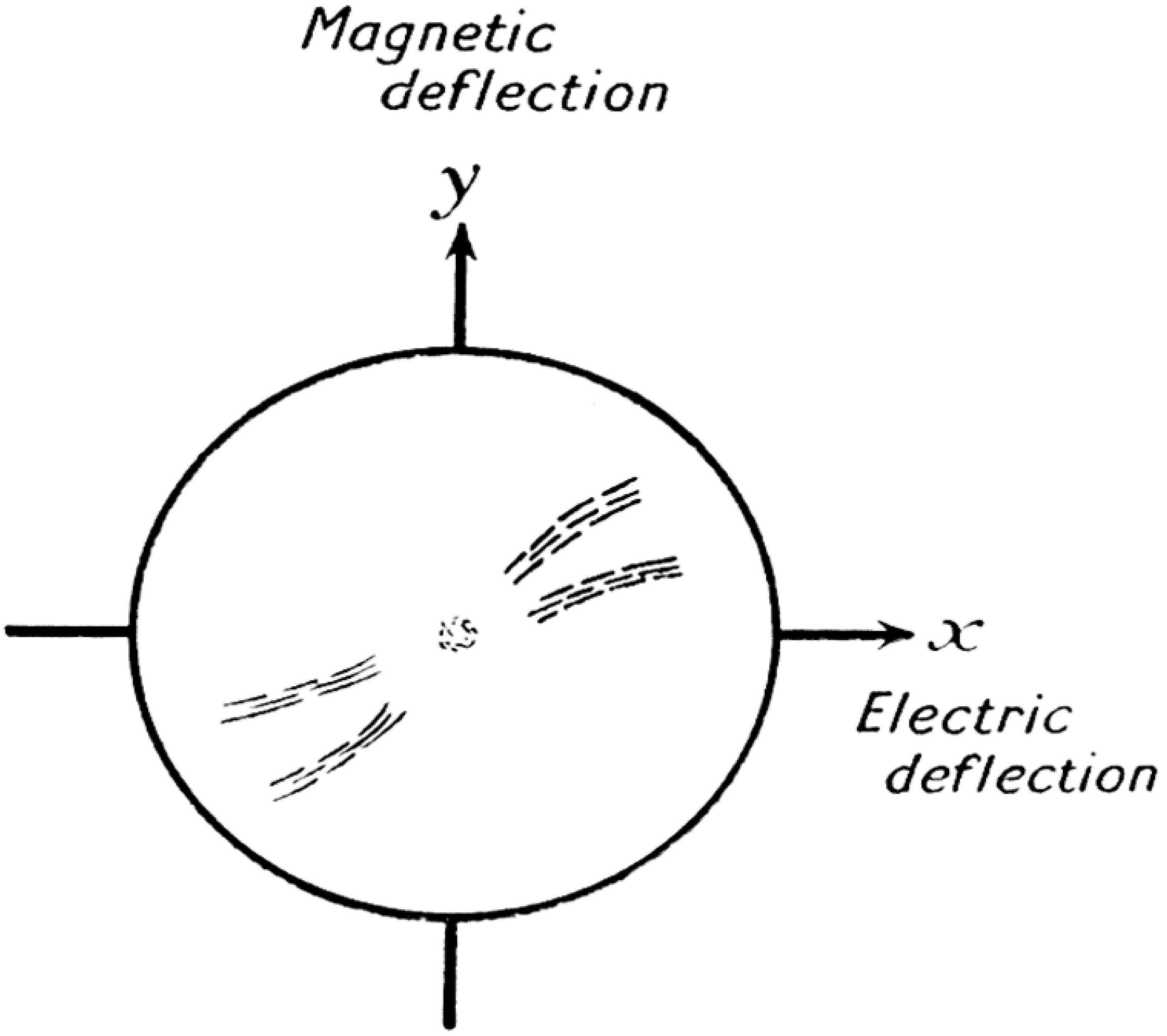


FIG. 31. Diagram of the appearance of the fluorescent screen with hydrogen parabolas.

$x$ = deflection due to electric field
$y$ = deflection due to magnetic field

Then $x = k \cdot \dfrac{Ee'}{m'v^2}$, and $y = k' \cdot \dfrac{He'v}{m'v^2} = k' \cdot \dfrac{He'}{m'v}$.

Hence
$$\frac{y^2}{x} = k \cdot \frac{H^2e'}{Em'} = C \cdot \frac{e'}{m'},$$

or $y^2 = C \cdot \dfrac{e'}{m'} \cdot x$, which is the equation to a parabola.

The value of the constant $C$ depends on the dimensions of the apparatus. It includes the length of the pole faces traversed by the positive ions and the distance of the poles from the fluorescent screen. As a first approximation it will be enough to assume that the electric and magnetic fields between the poles are uniform, when the equation becomes :

$$y^2 = \frac{ne'H^2}{m'E}\left(K + \frac{L}{2}\right) L \cdot x$$

where $K$ is the distance of the near edge of the poles from the screen,
$L$ is the length of the pole faces,
$n$ is the number of charges possessed by the ion under measurement. $n$ is 1 for hydrogen.

In the author's apparatus $L = 4$ cm., $K = 26$ cm.

Hence $\dfrac{e'}{m'} = \dfrac{Ey^2}{112H^2x}$, where $E$ and $H$ are both in electromagnetic units.

In a particular experiment with hydrogen in the tube

$E = 240$ volts $= 2{\cdot}4 \times 10^{10}$ e.m.u.
$H = 340$ oersteds.
$x = 1{\cdot}1$ cm.
$y = 2{\cdot}0$ cm.

whence
$$\frac{e'}{m'} = \frac{2{\cdot}4 \times 10^{10} \times 4}{112 \times 340^2 \times 1{\cdot}1}$$
$$= 9{,}970 \text{ e.m.u./gm.}$$

The accepted value for $\frac{e'}{m'}$, for protons is $9{\cdot}58 \times 10^3$ e.m.u./gm. It will be noticed that the precise measurement of the strength of the magnetic field is of great importance.

## CHAPTER V

# THE TRANSMUTATION OF LITHIUM

THE idea of the transmutation of the elements is at least as old as Aristotle, although by the term *element* he meant a property of matter rather than a distinct species of matter. The process of converting less valuable into more valuable matter has an obvious and legitimate appeal. It engaged the attention of the early chemists, who were sometimes deceived by small residues of gold or silver produced in smelting operations. Some few of the alchemists seem to have practised wilful deceit for the purpose of gain. With the rise of modern chemistry the idea grew up that the chemical elements as we know them now were unalterable by any process at our command. This view was held until the discovery of radioactivity, when it was found that transmutation is a naturally occurring process, for the elements uranium, radium and thorium are slowly being transformed into helium and lead. In 1903 Rutherford and Soddy explained the radioactive process as the spontaneous disintegration of the parent atom, much energy being liberated in the process and new atoms being formed. Thus a radium atom gives one of radon and an $\alpha$-particle, which is a helium atom that has lost two electrons. Natural radioactivity proved to be entirely beyond the control of scientists. It could neither be started, hastened, slowed nor stopped.

It became apparent to Rutherford, and later to others, that the identity of the chemical elements depended on a central nucleus and particularly upon the electric charge borne by the nucleus. If the charge on the nucleus could be altered the original atom would lose its identity and would become a different element. Since natural radioactive processes involved the liberation of much energy it seemed probable that a supply of energy at a high potential would be necessary to bring about a transmutation. In 1919 Rutherford found a means of altering the nuclear charge of certain elements by bombarding them with fast $\alpha$-particles from radium *C*. Nitrogen was converted into oxygen ($O^{17}$) and a proton of unusually long range, but the number of atoms affected by the bombardment was very small and the change could only be detected by the use of the most sensitive devices. Other energetic particles besides fast $\alpha$-particles were tried and it was found by Cockcroft and Walton in 1932 that protons accelerated by an electric field of about 120,000 volts could also bring about transmutations. Other sources of high potential energy were used and other ways of accelerating charged particles were developed. To-day some transmutations can be carried out to give weighable quantities of the product, but the processes employed require much energy and are therefore expensive.

A modification of Cockcroft and Walton's transmutation experiment can be made to yield visible results in the laboratory. Protons are accelerated in a glass tube by the application of a potential difference of 50 Kv. or more. The positive ray apparatus described on p. 44 may be used, provided that the fluorescent screen tube is changed for a tube containing the lithium target on which the stream of protons is to fall. Arrangements must be made for any $\alpha$-particles produced in the transmutation to escape from the apparatus into the air and to make their presence known by striking a fluorescent screen, or in some other way.

The electric and magnetic fields are not required and the insulated parts of the magnet are connected by earthing wires to the cathode. The waxed joint by which the fluorescent screen is sealed to the apparatus is heated with a small flame, temporary coils of compo-tubing carrying a current of cold water being used to prevent heat from reaching the waxed joints of the pole pieces. The screen tube is removed. In its place is fixed a metal tube of the shape illustrated in Fig. 32.

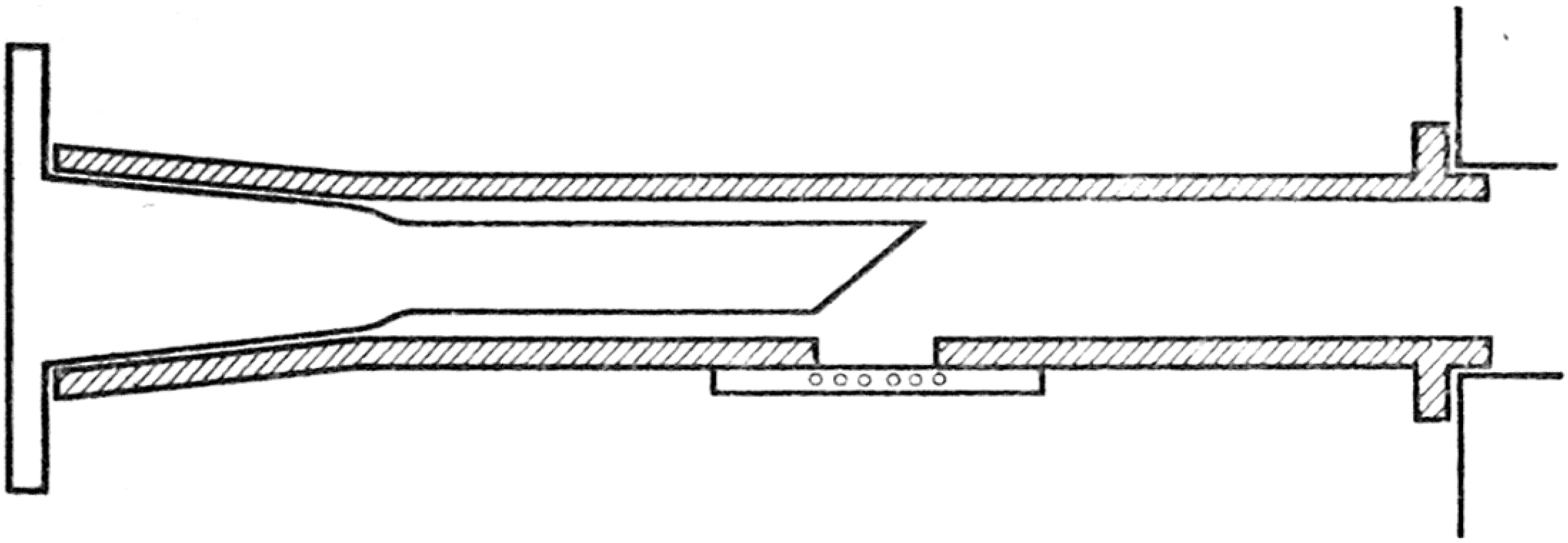


FIG. 32. Metal tube for transmutation of lithium, which is placed on the oblique surface of the central rod. The parallel wires serve to support a very thin mica window.

The circular hole is made by filing and is covered with a rectangular plate silver-soldered in position. This plate also has a hole 1 cm. in diameter in it, but four or five nickel wires are laid across it in grooves and are soldered in place. These wires serve to support a very thin mica window which is made by carefully splitting a piece of mica and cutting to shape with scissors. The flake of mica is split off by inserting a needle point under a suitable thin ragged edge of the mica sheet and carefully working it forward until a sufficient area of mica of uniform thickness is freed from the parent crystal. The flake should be as thin as possible and must not be cracked. It is cut to shape leaving an overlap of 3 or 4 mm. round the hole and is laid over the nickel wires, its seating having previously been given a thin layer of vacuum wax, such as Everitt's or Edwards' W.E.3. On warming with a very small flame the wax is melted to the mica and to the brass supporting plate, care being taken that the wax has run over the edges of the mica and that no channels remain through which air can get into the apparatus when it is exhausted. Inspection of this seal should be made with a hand lens if there is any doubt of its efficiency. The thinnest mica sheet that can be conveniently handled can withstand atmospheric pressure if it is adequately supported in the way described.

The conical plug of solid brass is made of such a length as to bring its sloping end opposite the window when it is waxed in position. The correct orientation of this plug should be indicated by making a saw-cut on the plug and the tube, to facilitate reassembly. The sloping end of the plug has an undercut groove on its face into which a thin slice of lithium metal can be pressed. The surface of the lithium is cleaned with the blade of a knife or a small file immediately before the plug is inserted, the wax seal is completed as quickly as possible and the pumps are started as soon as the seal is cold.

Observation of the $\alpha$-particles is made by means of a small lens of focal length about 4 cm., which is supported at the correct distance from a zinc sulphide screen. The fluorescent material should be thinly spread on a thin sheet of glass and should have the minimum of afterglow. The screen is placed 1 or 2 mm. from the mica window, the fluorescent substance being turned towards the mica. A rubber or velvet ring round the lens will allow the observer to feel his position with regard to the lens when making observations in the dark.

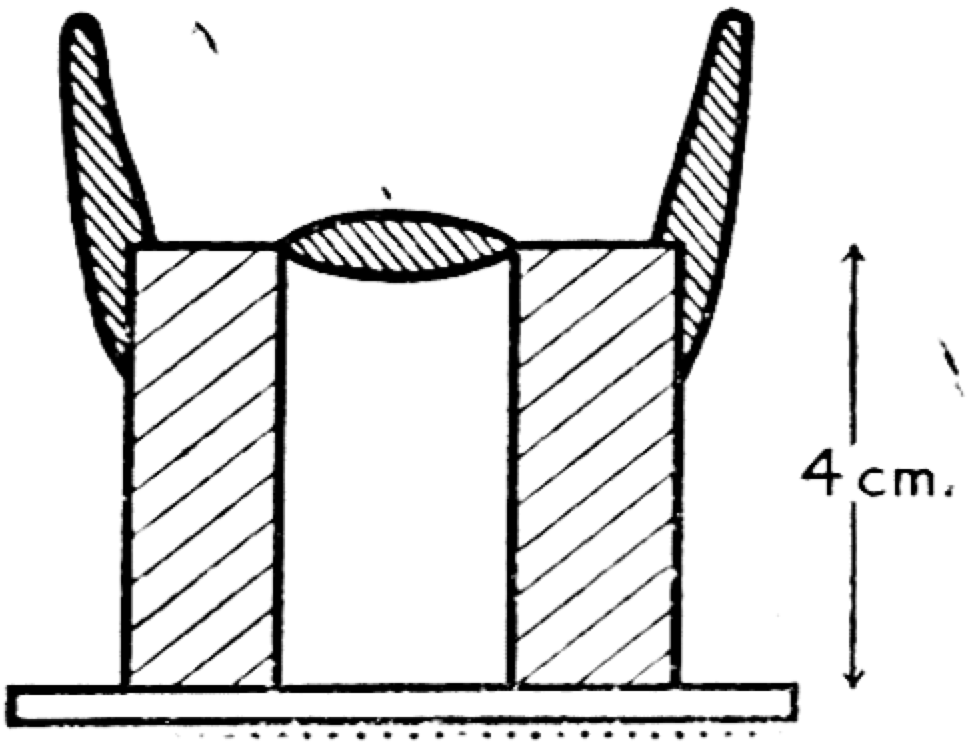


FIG. 33. Small lens arranged as eyepiece at its focal distance from a zinc sulphide screen with short afterglow.

To make an observation of the transmutation of lithium and a proton into two $\alpha$-particles, the apparatus is exhausted to an X-ray vacuum or better and is then flushed out once or twice by admitting hydrogen and re-exhausting. During this process the observer must dark-adapt his eyes and may test their condition by the use of a spinthariscope. When dark-adapted a careful search of the screen is made for spurious flashes due to contamination or stray particles. An estimate over five minutes or so of the number of these background flashes should be made, as it does not seem to be possible to get screens that are entirely free from them, even when new. If the background count is due to radioactive atoms embedded in the screen material the flashes will always appear in certain places in the same small area of the field of view and can soon be recognized. Flashes on other portions of the screen which occur when the accelerating potential is applied will probably be due to $\alpha$-particles.

When all is in readiness some hydrogen is admitted and the coil is turned on. As soon as the positive column has gone from the discharge tube flashes may be observed on the screen, their number depending in large measure on the applied potential. If a needle valve is employed it is possible to keep the hydrogen pressure fairly steady, but this is more difficult to do if the hydrogen is introduced through a palladium tube. The counting of flashes is tiring in these circumstances, but observation should be continued for five minutes to ensure that the number of background flashes is considerably exceeded. Using a 10-inch coil, six to ten flashes per minute have been observed with a fresh lithium target in excess of the background count. It may be concluded that the transmutation of lithium and protons into helium has been witnessed.

$$Li^7 + H^1 = 2\ He^4.$$

The details of this experiment are largely in accordance with those given by J. B. Hoag in *Electron and Nuclear Physics.* The method can be made much more sensitive by employing a Geiger counter and it is stated that this transmutation has been detected with as low an accelerating potential as 13 Kv.

# CHAPTER VI

# THE BROWNIAN MOVEMENT

DURING the first few decades of the nineteenth century great advances were made in both theoretical and applied optics. Fraunhofer began to make optical glass of greatly improved quality. Achromatic objectives, which had been commercially available for telescopes since 1757, were being made for use with microscopes, but not with much success until Chevalier of Paris in 1820 showed that if the plane side of a cemented achromatic pair is presented to the object to be magnified greatly improved results are obtained. In 1830 J. J. Lister, the father of Lord Lister, constructed an achromatic objective of the type that is still in use for medium powers (1 inch and $\frac{2}{3}$ inch). The development of the modern compound microscope had begun, attended by great advances in biology.

In 1827 the English botanist Robert Brown described the erratic and haphazard movement of pollen grains suspended in water which is to-day known by his name. Not much interest was taken in this discovery at the time, but Wiener in 1863 and others later showed that the movements were independent of vibration or of convection currents. In fact the Brownian movement never ceases and the hypothesis has been held for many years that it is due to the random bombardment by molecules of the suspending fluid of those visible particles which are small enough to be rotated or translated by such impacts.

The importance of the Brownian movement lies in the support it gives to the molecular kinetic theory. In particular it has led to methods of measuring Avogadro's number $N$, the number of molecules in 1 gm. molecule of a gas. The values of $N$ obtained by measurements of Brownian movement are in accord with those deduced from other widely different independent phenomena. The work in question was done by Jean Perrin at the Sorbonne about the year 1910 in a series of classical researches which make fascinating reading. He carried out measurements of Brownian movements involving observations of :

(*a*) the vertical distribution of particles ;
(*b*) the displacements of particles ;
(*c*) the rotations of particles ;
(*d*) the diffusion of particles.

(*a*) Vertical distribution of particles in the gravitational field. Perrin showed that small spheres of gamboge and mastic remained permanently suspended in various liquids, thus constituting an atmosphere whose concentration followed the same law as that for the diminution of the density of the air with increase of height. The particles are pulled downwards by gravity and tend to diffuse upwards owing to their Brownian movement. An equilibrium is attained at all levels.

Perrin measured the mass of his particles, which were selected so as all to be of very nearly the same radius in any one experiment and also measured their concentrations at different heights. From a comparison of the heights of the columns of air and of his solutions which gave a decrease in density of one half, he was able to calculate the number of air molecules in 1 c.c., and hence Avogadro's number. The expression used is :

$$2{\cdot}3 \log \frac{n_o}{n} = \frac{N}{RT} \cdot m\left(1 - \frac{d}{D}\right) gH.$$

where $\frac{n_o}{n} = \frac{1}{2}$ ; $m$ is the mass of one particle ; $d$ is the density of the suspending medium ; $D$ is the density of the material of the particle ; and $H$ is the height required for a fall of density from $n$ to $n_o$. Perrin's value for $N$ from these determinations was $6{\cdot}8 \times 10^{23}$.

(*b*) The displacements of particles. In the years 1905 and 1906 Einstein published a number of papers in which he gave a detailed analysis of the Brownian movement, making the assumption that it is completely irregular. That this is so has been amply confirmed by experiment. Einstein showed that the particles of an emulsion, such as that in which Brownian movement can be observed, diffuse like those of a true solution and that the coefficient of diffusion $D$ is equal to one half of the number that measures the activity of the Brownian movement.

$$D = \tfrac{1}{2} \cdot \frac{x^2}{t},$$

where $x^2$ is the mean square of the projection of the horizontal displacement of the particle in time $t$.

The displacements of various particles were observed, using suspensions in media of different viscosities, and a number of values of $N$ were deduced by Perrin and his co-workers by the use of Einstein's equation :

$$N = \frac{t}{x^2} \cdot \frac{RT}{3\pi a \eta},$$

where $x$ is the displacement in time $t$ ; $a$ is the radius of the particle ; and $\eta$ is the coefficient of viscosity of the suspending medium. Perrin gave the result $N = 6{\cdot}9 \times 10^{23}$.

(*c*) The rotations of particles. Perrin prepared some relatively large particles of mastic which contained visible inclusions. These were suspended in 27 per cent. urea solution and were carefully observed by means of a vertical microscope. The rotations produced by Brownian movement were measured and Einstein's equation for rotations was applied to the results. The equation is :

$$N = \frac{t}{A^2} \cdot \frac{RT}{4\pi a^3 \eta},$$

where $A^2$ is one-third of the mean square of the angle of rotation in time $t$. The value given by Perrin for $N$ was $6{\cdot}5 \times 10^{23}$.

(*d*) The diffusion of particles. A third experimental determination of $N$ from Einstein's equations was made by direct measurements of diffusion, although the effects of diffusion counteracted by gravity had already been used in the experiment on vertical distribution. In these experiments the gamboge grains were suspended in dilute glycerine and were allowed to stick to a partition in the liquid when they reached it by diffusion. The partition was photographed twice a day for several days, the temperature being rigorously controlled. Einstein's equation $N = \frac{RT}{D} \cdot \frac{1}{6\pi a\eta}$ was used, the value given by Perrin being $N = 6{\cdot}9 \times 10^{23}$.

An account of Perrin's brilliant work on the Brownian movement is to be found in his well-known book *Atoms*, translated by D. Ll. Hammick, first published in English in 1916 by Constable & Co. It is recommended that every chemist should become familiar with Perrin's own account of this excellent example of scientific method, if a copy of the book can be obtained.

It is very simple to make arrangements for demonstrating Brownian movement and every science student should be familiar with it at first hand. The following four methods of making the movement visible have been used in the school laboratories and although details will differ according to the apparatus available, ordinary school equipment and perhaps a little ingenuity can be made to give successful results. Brownian movement may be shown in the following circumstances :

(1) Solid particles suspended in liquid with vertical illumination.

(2) Solid particles suspended in liquid with horizontal illumination.

(3) Liquid particles suspended in gas with horizontal illumination.

(4) Gas bubbles in liquid with vertical illumination.

(1) and (2) *Solid Particles*

A microscope is required giving a magnification of a few hundreds, say a $\frac{1}{6}$-inch objective and a × 10 eyepiece, which gives a magnification of about × 400, and a drop of very dilute gamboge paint from an ordinary water colour paint-box. Place a cover slip over the drop of dilute gamboge suspension. Observation will be satisfactory until evaporation at the edge of the cover slip begins to cause streaming of the liquid towards the region of greatest evaporation. More liquid may then be added. Another easily available suspension is provided by Indian ink, which contains finely ground particles of carbon. The ink should be very much diluted with water.

If the period of observation is to cover some hours it may be worth while to make a sealed cell, either by using a cavity slide, fixing the cover slip with a ring of gold size, or by building a wall of gold size on an ordinary 3 × 1 microscope slide and covering as before. Such a slide may continue to show Brownian movement for several days if the particles are small, but it is not easy to make a suspension of particles of the right size to be visible at a magnification of this order which will remain indefinitely in motion.

For projection purposes a microprojector with vertical illumination through the microscope is desirable unless the making of a sealed-off slide can be timed to coincide with the demonstration. A very good substance for projection is rutile, $TiO_2$, as it has a high refractive index and gives a good contrast on the screen. A small amount of the solid is finely powdered in an agate mortar and shaken with water. The suspension takes some days to settle and presumably the lower layers of the column of liquid contain the smallest particles in permanent suspension. Rutile is also excellent for individual observation with the microscope. The particles give a most fascinating display of rotation as well as of random linear movement.

To show the movement of the particles of metal suspended in an apparently clear solution of colloidal silver or gold the ultra-microscope arrangement must be used. The magnification of the viewing microscope need not exceed × 250 but the transverse illumination must be as intense as possible and should consist of a narrow beam which is only a few tenths of a millimetre deep. A $\frac{2}{3}$-inch objective and a × 15 eyepiece will do quite well, or if a higher magnification is desired, water immersion of the objective may be used. The red silver sol made by the reduction of silver nitrate with ferrous sulphate and sodium citrate is very suitable, as it is sufficiently stable to last for days without being precipitated. In his *Textbook of Inorganic Chemistry*, Partington gives these instructions for preparing the red sol. "To 100 c.c. of a 10 per cent. solution of silver nitrate add quickly a solution formed by mixing 100 c.c. of a 30 per cent. solution of ferrous sulphate and 100 c.c. of a 40 per cent. solution of sodium citrate, the mixture being carefully neutralized with soda before addition to the silver solution. A lilac precipitate of silver is formed which is filtered off and washed with a 5–10 per cent. solution of ammonium nitrate. It is then soluble in pure water forming a red transparent solution."

The sol is contained in a small circular glass cell made by cutting the bottom off a specimen tube. The cell may be about 2 cm. in diameter and about 1 cm. high. The source of horizontal illumination may be a pointolite lamp or even better a Siemens compact source tungsten filament lamp. If these are not available a 24- or 48-watt headlamp bulb will serve. Some care should be given to the system of condensers, slit and projection lens to ensure that the depth of liquid illuminated is small, or there may be a good deal of diffuse background illumination which will make the moving particles difficult to see. The beam of light may be further defined and stray light may be reduced by placing a vertical screen with a small horizontal slit in it near the cell on the microscope stage. Such a slit is readily made by waxing two pieces of safety razor blade over a small hole drilled in a piece of ebonite of a few millimetres thickness. If a $\frac{2}{3}$-inch objective is used there will be plenty of clearance between the lens and the liquid, but an objective of shorter focus ($\frac{1}{4}$ or $\frac{1}{6}$ inch) may be used immersed. Some trouble may be encountered owing to convection currents in the liquid set up by the heat of the illuminating beam, but these can be reduced by ensuring that the light passes through the middle of the cell and can be eliminated by interposing a water-cell between the source of light and the slit. The use of a water-cell cuts down the intensity of illumination considerably.

### (3) *Liquid Particles*

Several suitable cells have been designed for showing Brownian movement of the particles of tobacco smoke. One design at least is at present on the market. It is not necessary to use metal for the body of the cell. Ebonite will do quite well and is easier to work with hand tools. The forms of cell illustrated below require only two pieces of ebonite and other materials which are readily to hand.

C. F. G. Searle's design of cell gives very good results with a $\frac{2}{3}$-inch objective but the illuminated particles are too far below the cover slip for the higher powered objectives to be employed. It may be of use here to include a table of data referring to a few of the usual microscope objectives, as it is feared that some chemists handicap themselves in their teaching by lack of familiarity with the microscope. The following table is abridged from *Practical Microscopy* by

| Description of objective *i.e.* focal length | | Magnification for 160 mm. tube length | Approximate working distance in mm. |
|---|---|---|---|
| ins. | mm. | | |
| 1 | 24 | 6·4 | 14 |
| $\frac{2}{3}$ | 16 | 10 | 8 |
| $\frac{1}{3}$ | 8 | 20 | 2 |
| $\frac{1}{6}$ | 4 | 40 | 0·5 |
| $\frac{1}{12}$ | 2 | 80 | 0·2 |

Martin and Johnson. The total magnification given by a microscope may be calculated approximately by multiplying the primary or objective magnification by that of the eyepiece.

Searle's cell for showing Brownian movement in tobacco smoke is made of brass. Three cylindrical chambers are bored in a solid brass cylinder. A slit in this cylinder and a hole connecting the chambers to one another admit a narrow beam of light. The chambers should be blackened inside. Another small hole is bored at right angles to the light path for the admission of smoke. The cylinder fits accurately into a short length of brass tube closed at the bottom with a brass plate

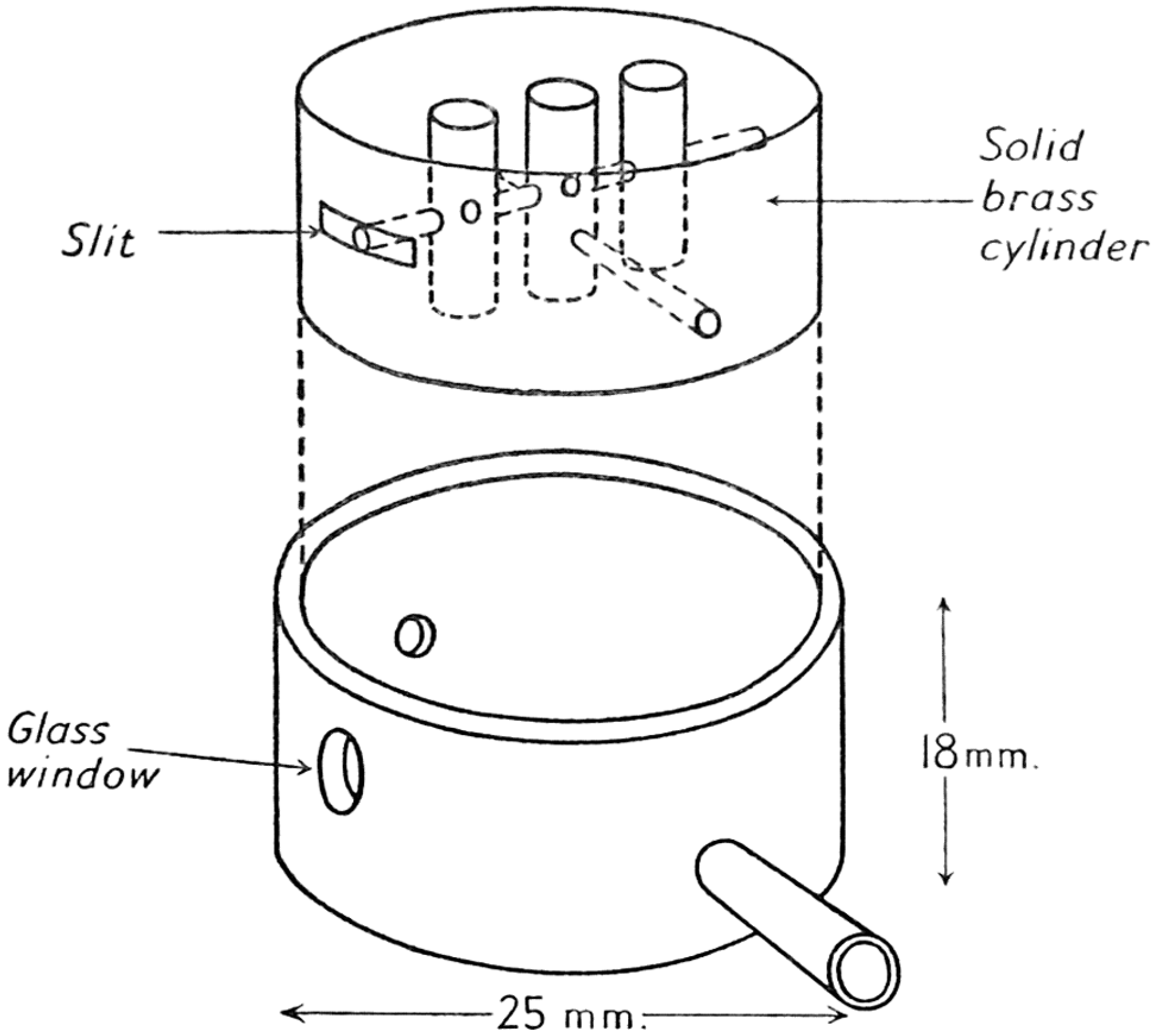


FIG. 34. Exploded view of Searle's cell for showing Brownian movement in tobacco smoke. Transverse illumination is used.

and at the top with a thin cover glass. A small glass window is waxed in place to admit light to the slit. A rubber teat, or a short length of rubber tube closed at one end, is attached to the side tube. This is squeezed and released when the cell is immersed in smoke, sufficient of which enters the cell to show Brownian movement for ten minutes or more. A × 15 eyepiece should be used, as the working distance of the higher powered objectives is too short to reach the region of illumination. There is no streaming of the particles with this design of cell.

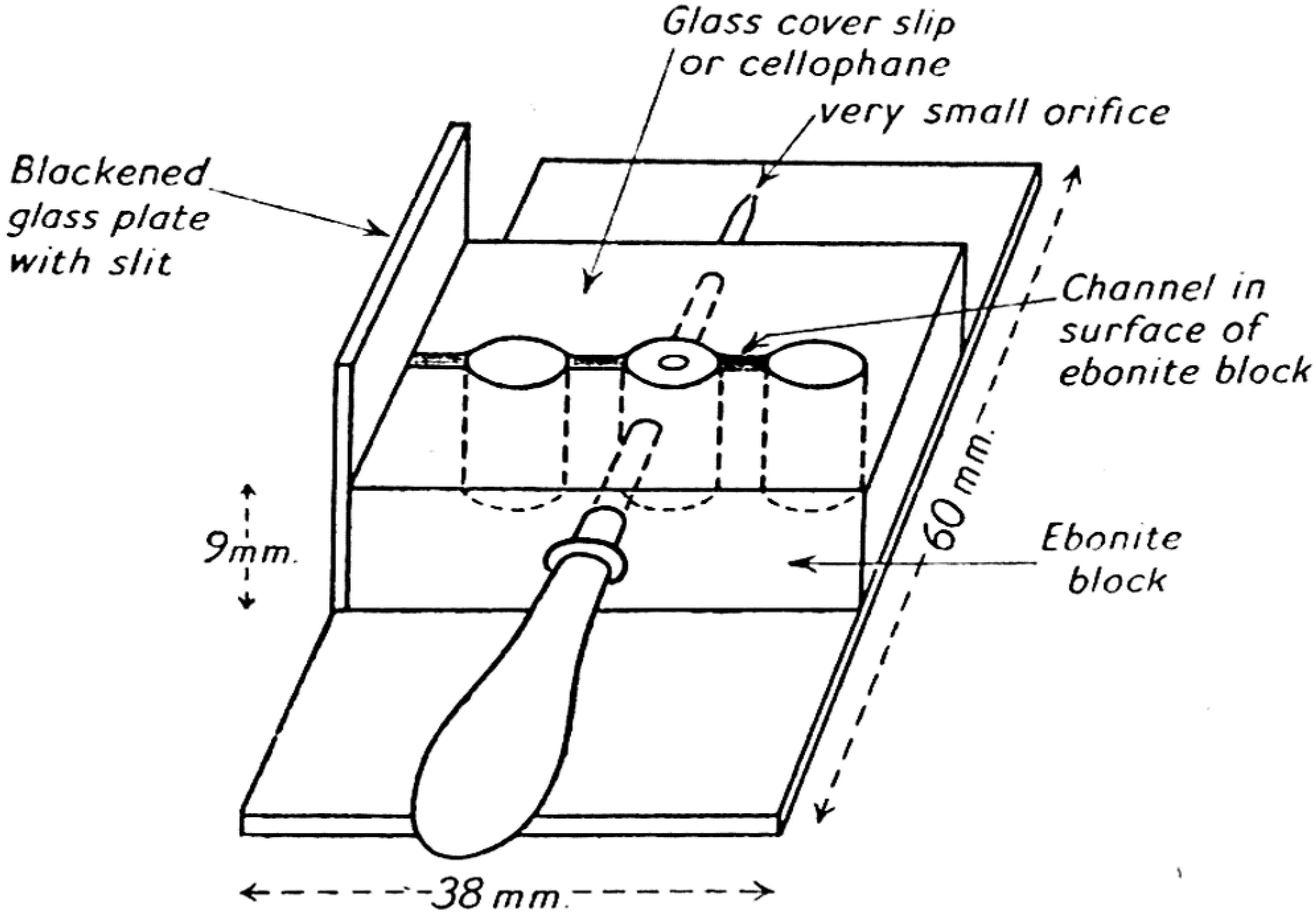


FIG. 35. Modification of Searle's cell in ebonite for use at higher magnification.

If higher magnifications are required with the ultramicroscope arrangement, provision must be made to use a thin cover slip or a sheet of cellophane lying just above the illuminated beam. A modification of Searle's cell provides the required conditions. It may be made of ebonite or of any suitable material. In one design a single chamber is used and the light is admitted just below the transparent cover, which may be either a thin microscope cover slip, or a piece of cellophane, such as is used for wrapping food. Cellophane is preferred, as the glass cover slip is exceedingly fragile and would readily be broken by contact with the microscope objective. The second form of cell is a close imitation of Searle's cell in that it has three chambers. These are connected by a transverse channel which is cut just below the cover glass. The slit may be cut with the point of a knife in a film of Edwards' W wax, which is melted on a small piece of sheet glass and serves to define the beam of light entering the cell and to exclude stray light. The dimensions of these cells are shown in the diagram. Smoke is admitted as before.

With this apparatus the movements of the particles can be very much enlarged. A $\frac{1}{3}$-inch or a $\frac{1}{4}$-inch or even a $\frac{1}{6}$-inch objective can be used, which last with a × 12 or × 15 eyepiece will give magnifications of the order of × 500. Intense illumination is necessary. An interesting effect can be seen at these higher magnifications when streaming occurs. Owing to the viscosity of the air, the particles in the layer of gas just below the cellophane can be seen to be streaming relatively slowly, but the speed of streaming is seen to increase as the focal plane is moved down into the body of gas and away from the gas-cellophane interface.

It is probable that many other designs of smoke cell will suggest themselves to the reader. They are easy to make even if machine tools are not available and the cost is negligible.

### (4) *Gas Bubbles*

One of the most remarkable and striking demonstrations that can be given is provided by the gas bubbles that are often to be found in the liquid inclusions in quartz. Slices of quartz which show Brownian movement can be purchased, but if suitable quartz crystals are available, the labour involved in cutting and grinding them down to a thickness of a few hundredths of a millimetre is well repaid. The section, which is ground first with emery and water and later with tin dioxide and water as abrasives, does not have to be polished, as it is made optically clear by the balsam used to stick it to the slide and to the cover slip. The drawback to this work is that a good deal of time may be spent on making the sections only to find that they have no liquid inclusions containing bubbles of gas. The bubbles are so small that they cannot profitably be observed with an objective of longer focal length than $\frac{1}{6}$ inch. Even so, it may be necessary to hunt for some time to find a moving bubble, but they are so fascinating when found that the time is well spent. The best results are obtained with a $\frac{1}{12}$-inch oil immersion objective and a × 10 or × 15 eyepiece. A good example of the phenomenon is delightful to watch and should be demonstrated. It is not easy to find a particular bubble once the slide has been moved, unless the microscope has a mechanical stage. Microprojection at these high magnifications is quite possible in a darkened room, provided the optical system is of sufficiently good quality and sufficient light can be brought to bear on the lens of the objective. The field of view may be a foot or two in diameter.

Another method of demonstrating Brownian movement of liquid drops suspended in air is described below under the heading *Millikan's apparatus*.

# CHAPTER VII

# MILLIKAN'S APPARATUS

Benjamin Franklin alone among those who founded the early theories of the nature of electricity seems to have had the idea of electrical particles. The more usual notion was to regard electricity as having the nature of a continuous weightless fluid, or of two fluids having opposite properties. In the two fluid theory equal amounts of positive and negative electricity were supposed to neutralize one another, leaving nothing behind them. For more than a hundred years the attention of physicists was turned to a consideration of the mode of interaction of electric charges rather than to the nature of the charges themselves and it was not until 1871 that we find a physicist making much use of the idea of charged particles to explain electrical phenomena. This was done by Wilhelm Weber in his theory of electromagnetism. The laws of electrolysis had been formulated by Faraday in 1833 but at the time of their publication they did not call insistently for a particle theory of electricity, although the atomic theory of matter was by then well known and was accepted by many workers. Even if the gram equivalents of all ions had the same total charge, it was felt to be gratuitous to assume that each monovalent ion had one unit of charge. All that was known for certain was that the total charge on the electrode was constant for the liberation of 1 gm. equivalent of ions, not that this total of charge was equally distributed between the ions which carried it. But the idea of a unit electrical particle was in the air. Maxwell had considered it in 1873. The next year G. Johnstone Stoney not only enunciated the theory of the atomic nature of electricity quite clearly, but also gave an estimate of the value of the unit charge in electrostatic units.

For a time electrolytic conduction was thought to be of a different kind from metallic conduction and the two phenomena were not explained in the same terms, but with the discovery of the ionization of gases and of their powers of conduction, it was proved by J. J. Thomson and his collaborators that matter of all kinds could be made to yield a stream of negatively charged particles whose speed could be measured and whose mass and charge were the same from whatever kind of matter they came. The name *electron* had been given by Johnstone Stoney to these particles in 1891, before J. J. Thomson's quantitative work had been carried out. It was also shown by workers under Thomson's guidance that the electron, whose existence he had confirmed by experiments on the conduction of gases, was identical with the unit negative charge carried by a univalent ion in electrolysis. It is easy enough to measure the quantity of electricity required to liberate 1 c.c. of hydrogen gas in an electrolysis experiment. If each hydrogen atom is associated with the same amount of electricity, which may be called $e$, and if there are $n$ atoms of hydrogen in 1 c.c. of gas, the amount of electricity in question is the product $ne$. It is clear that if $n$ is known a value for the charge $e$ can be calculated. It was the achievement of J. S. E. Townsend at Cambridge in 1900 in measuring the diffusion coefficients of gaseous ions that led to a value of $ne$ for these ions which was nearly the same as that derived from electrolysis experiments. The conclusion was that the particles of electricity involved in both cases were the same and rough estimates of the magnitude of $e$ in electrostatic units were soon forthcoming, but none of them was very precise, although they were reasonably concordant and left little doubt in the minds of physicists of the existence of negative electrical particles or electrons as constituents of all matter.

During the course of the work on the conduction of gases at Cambridge a most fruitful experimental method had been developed. In 1897 Townsend had obtained a value for $e$ by measuring the charge on a cloud of water drops produced on the bursting of the bubbles of hydrogen which are given off by a metal dissolving in acid. It was soon realized that ionized gases contain nuclei on which water drops are easily condensed, thus giving a cloud, and in 1903 H. A. Wilson, also at the Cavendish laboratory, formed a cloud between the parallel plates of a condenser which was charged to a known potential. With this apparatus the charged drops could be controlled and the effect of gravity upon them could be counteracted by the force produced by the electric field, but one of the difficulties with all these experiments in which water drops were used was evaporation. The work was taken up in the United States of America by R. A. Millikan of the University of Chicago and the problem was finally solved by the substitution of oil drops for those of water. His research lasted from 1909 to 1916 and was so complete and so brilliantly executed that it has left no doubt whatever in the minds of physicists that electricity may be regarded as discontinuous in nature. Many consistent results were obtained which indicate that negative electricity occurs in ionized gases in unit quantities and that a fraction of this unit amount of electricity is not encountered. So fundamental is this measurement of the unit electric charge and so easy is it to perform a simplified version of Millikan's experiment, that all serious students both of chemistry and physics should be given the opportunity to make the measurement for themselves. They should also read Millikan's own account of his work.*

A form of Millikan's apparatus which has been developed for use in schools is described here. The cost of the materials is negligible, provided a short-range telescope with an eyepiece scale is available. If such an instrument is not available, excellent telescopes can be obtained from Messrs. W. G. Pye & Co. Ltd. of Cambridge, for two or three pounds. The telescope should be mounted so that it can be moved along its own axis and also parallel to its own axis in a horizontal plane. The principle of the experiment is to produce a mist of fine oil drops by means of an ordinary atomizer and to allow some of them to fall through a small hole in the upper plate of a horizontal parallel plate condenser, whose electric field can be varied at will. The principle of the ultramicroscope is used to provide cross-illumination of the drops, some of which are charged by the process of atomizing, and to observe them against a dark background by means of the light which they reflect or scatter. Their rates of fall under gravity, or their speed in the opposite direction in the electric field, can then be found by timing their movement across selected divisions of the eyepiece scale, whose value in millimetres has been found at the range at which it is focussed. A 120-volt dry battery is all that is required to provide the electric field, with a suitable potentiometer for varying the potential across the plates of the condenser. The complete apparatus is shown in the figure (Fig. 36) and the details of its parts are described below.

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* *The Electron*, by R. A. Millikan: University of Chicago Press.

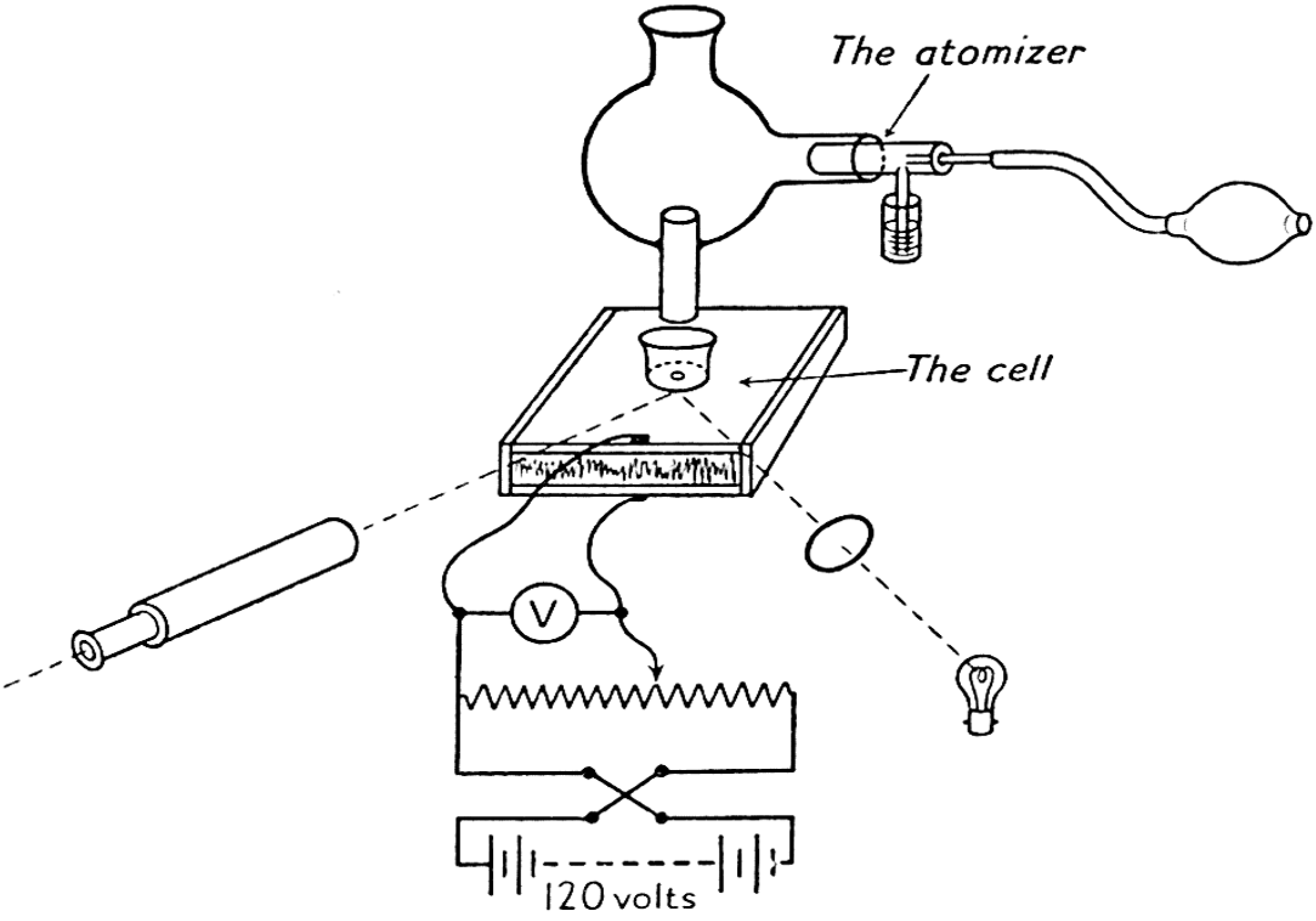


FIG. 36. Simple version of Millikan's apparatus. The cell, the atomizer, the electric circuit and the optical system are shown.

The cell consists of two rectangular plates of brass, about $\frac{1}{16}$ inch thick, of such a size as to leave a square space 5 × 5 cm. between them when separated by their distance pieces. The upper plate has a hole not more than 1 mm. in diameter drilled through it at its middle point and the two plates are kept about 4 mm. apart by strips of ebonite or other insulating material placed between them along two opposite edges. The parts of the cell may be fixed together by means of shellac dissolved in alcohol. The distance apart of the plates must be accurately known and may be measured at this stage. A copper wire is soldered to each plate. The cell is then mounted on a piece of $\frac{1}{4}$-inch ebonite which has been drilled for fixing to a suitable wooden support. The upper brass plate is also covered with a piece of ebonite, but a circular hole is cut in this to allow a short length of glass tubing to provide a shield from air currents around the hole through which the oil drops are to enter the cell. The two open ends of the cell are then covered with strips of glass cut from a used photographic plate from which the gelatine has been removed. These glass strips are fixed in place with shellac and should seal the cell completely so that no air currents can affect the motion of the oil drops in the cell. Some care is then taken to mount the cell truly horizontal or else provision should be made in the usual

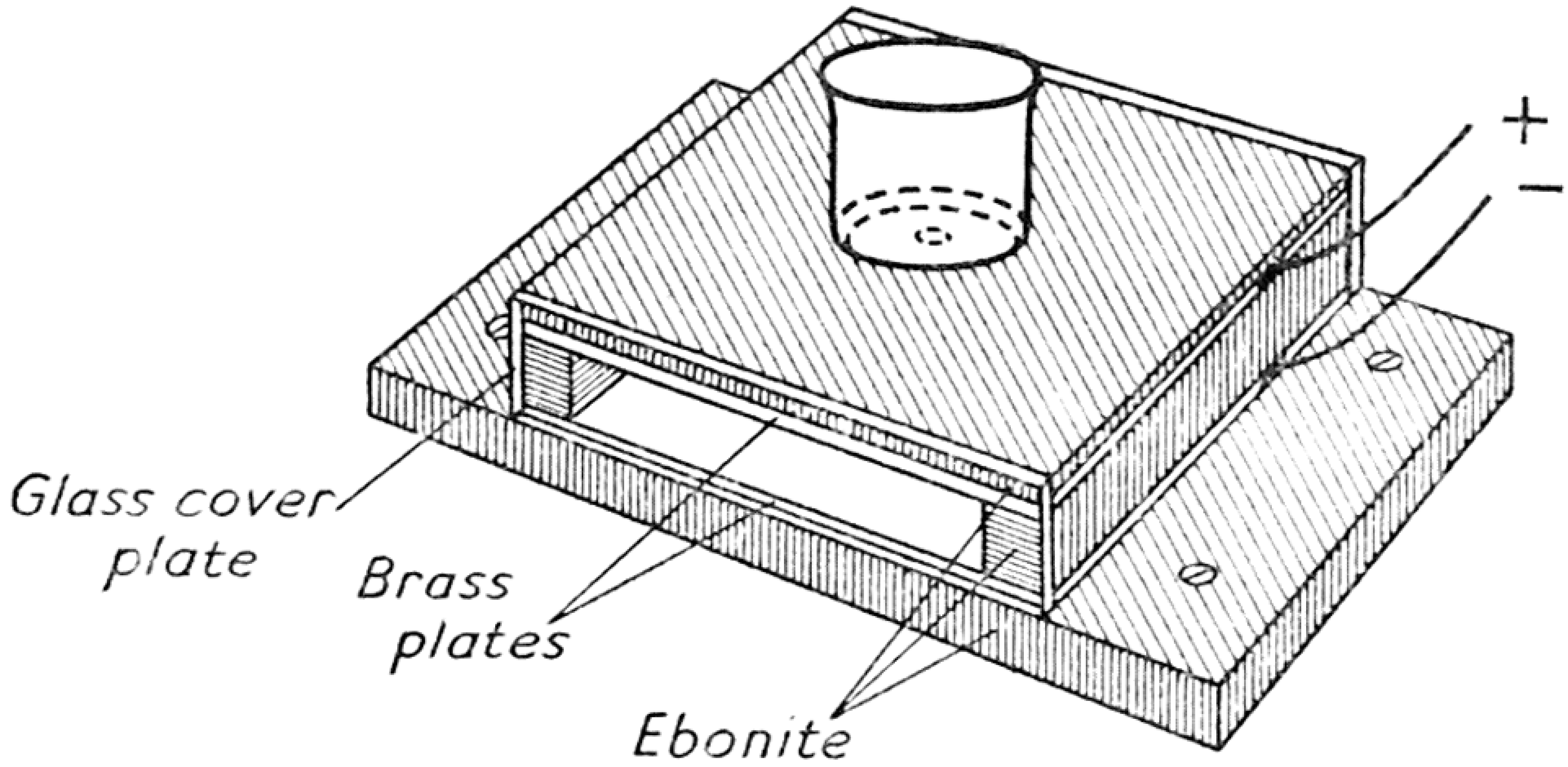


FIG. 37. Details of construction of the cell.

way for levelling it, as it is important that the electric and gravitational fields should be parallel. The cell can be made in the way described very quickly and with very simple tools. It is mounted firmly at such a height that a seated observer can comfortably spend a considerable time at the telescope (see Fig. 37).

The atomizer is of the conventional pattern. A rapid stream of air is blown across the open end of a vertical fine bore brass tube which dips into a small reservoir of thin oil. Clock oil or the brand known as 3 *in* 1 is suitable. The density of the oil at room temperature must be found. The spray of oil mist passes into a glass bulb having two open tubes along its vertical axis. The lower tube is arranged to protrude inside the bulb so that any oil which runs down the inner surface of the bulb is caught and prevented from blocking the hole in the upper condenser plate. On squeezing the rubber ball a cloud of oil drops, many of which are charged, is formed inside the glass bulb and a number of these drops fall through the hole in the upper condenser plate and become visible in the telescope.

The source of light may be an electric lamp of almost any kind. The light should be concentrated with a convergent lens, but if a bulb of low wattage is used a water cell can be dispensed with. The light should be directed to the area vertically below the hole in the upper condenser plate and sufficient of it should be reflected from the inner wall of the cell to illuminate the scale in the eyepiece of the telescope, but direct light from the source must be prevented from falling on the objective of the telescope if the drops are to be clearly visible. The most suitable positions of the telescope and the source of light are found by trial. The telescope may be of the type sold by Messrs. W. G. Pye & Co. Ltd., catalogue No. 9865 or No. 9870, with an eyepiece scale divided into 100 parts and numbered at every ten divisions.

The value in millimetres of the eyepiece scale at the range at which the telescope is being used may be found by means of a special dipstick, made to fit loosely in the hole in the upper condenser plate. It consists of a fine steel rod on which a spiral groove of $\frac{1}{2}$ mm. pitch is scratched in the lathe. This steel rod is inserted axially in a small brass disc to which a handle is attached. The dipstick is inserted in the hole in the upper condenser plate and its edge is sharply focussed in the telescope so that the spiral groove can be seen simultaneously with the eyepiece scale. Since the pitch of the spiral groove is known to be $\frac{1}{2}$ mm., the number of divisions of the eyepiece scale which correspond to $\frac{1}{2}$ mm. can be read off.

Many alternative methods of making this essential measurement will probably occur to the reader.

The potential difference between the condenser plates is provided by a 120-volt dry battery. A 10,000 ohm radio volume-control is used as a potential divider to provide any voltage between the maximum and, say, 20 volts. A double-pole knife switch with two of its terminals shorted is included in the circuit so that the field can be established or cut off at will. The shorting of the condenser plates ensures that there is no residual field. The circuit includes a voltmeter which should be tested for accuracy against a standard instrument.

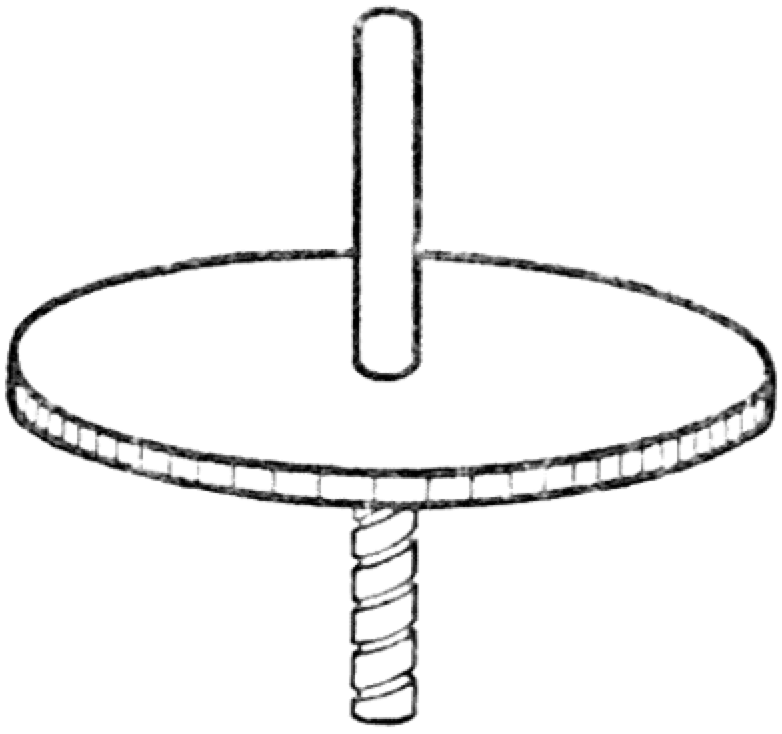


Fig. 38. Dipstick with spiral groove of $\frac{1}{2}$ mm. pitch.

The procedure for using the apparatus is first to focus the eyepiece of the telescope so that a sharp image of the scale is obtained. The value of the eyepiece scale in divisions per mm. is then found by inserting the dipstick or other graduated device into the hole in the upper condenser plate and illuminating it, the source of light and telescope being so disposed that the field of view is illuminated with sufficient reflected light to make the eyepiece scale visible, but so that it is not bright enough to impair the visibility of the oil drops when they are introduced. A few trials will serve to make this adjustment. A cloud is formed in the atomizer and when the oil drops enter the cell a difference of potential of 60 to 70 volts is established between the plates. Some drops will be accelerated but those that are uncharged will continue to fall in the gravitational field, which means that they will rise in the field of view. It must constantly be borne in mind that the image in the telescope is inverted. By manipulation of the electric field it is possible to choose a single drop and to allow all the others to reach the condenser plates. With a little practice it will be found that the selected drop can be kept in the field of view as long as the observer cares to watch it, especially if his telescope has an adjustment for fore-and-aft and also lateral movements, as the drop may move off the line of sight or go out of focus owing to Brownian movement. The smaller drops which show a time of fall of 30 seconds or so over ten eyepiece divisions are likely to be displaced in this way. There will also be a tendency for the drop to move out of the vertical and hence to go out of focus if the electric and gravitational fields are not parallel, a fault which can perhaps be eliminated by relevelling the cell. The time of fall, that is, the upward movement of the drop in the field of view, over ten or twenty eyepiece-scale divisions is then taken with a stop-watch which is started and stopped by the observer, but which is read and recorded by an assistant. The electric field is then put on and the speed of the drop when moving against gravity is recorded together with the applied voltage. A series of at least ten readings should be taken with the same drop and the average speed calculated. An average value of the applied voltage should also be found.

A second way of using the apparatus is to time the fall of a selected drop under gravity as before and then to find the voltage that must be applied to prevent the drop from falling. This gives a useful check on the other method, but whether the measurement of voltage is more accurate than the measurement of speed will depend on the quality of the instruments employed, on the skill of the observer and on other factors. Measurements of Brownian displacements may also be made with this apparatus.

The value of the charge on a particular drop can be computed from the following considerations. The fall of spheres through a viscous medium was investigated by Sir Gabriel Stokes in 1850. The law states that the resistance $R$, of a sphere moving slowly through a viscous medium is given by the expression :

$$R = 6\pi\eta a v,$$

where $a$ is the radius of the sphere, $v$ is the velocity and $\eta$ is the coefficient of viscosity of the fluid. It will be remembered that the coefficient of viscosity is the tangential force per unit area between parallel planes 1 cm. apart in the viscous medium, when one plane is moving with unit velocity relative to the other. If the sphere is acted upon by a force $F$, it attains a certain terminal velocity such that the resistance just balances the moving force. This terminal velocity is given by $v = \dfrac{F}{6\pi\eta a}$. If the force is the weight of the sphere,

$$F = mg = \frac{4\pi a^3}{3} (\rho - \sigma)\, g.$$

where $\rho$ is the density of the sphere and $\sigma$ is that of the medium. For an oil drop falling through air, $\sigma$ may here be neglected in relation to $\rho$.

Hence
$$m = \frac{4\pi a^3 \rho}{3} = \frac{6\pi\eta a v_d}{g}$$

or
$$m = \frac{4\pi}{3}\left(\frac{9}{2} \cdot \frac{\eta v_d}{g\rho}\right)^{\frac{3}{2}} \rho \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(i)}$$

the symbol $v_d$ denoting the velocity due to gravity of a drop of mass $m$ in the absence of the electric field. Then $v_d \propto mg$. Let the velocity of the same drop rising against gravity in an electric field $E$ be $v_u$. Then $v_u \propto Ee_n - mg.$, where $e_n$ is the charge on the drop.

Hence
$$\frac{v_d}{v_u} = \frac{mg}{Ee_n - mg},$$

and
$$e_n = \frac{mg}{Ev_d}(v_u + v_d) \quad . \quad . \quad . \quad . \quad . \quad \text{(ii)}$$

Substituting the value of $m$ found above in equation (i) and converting electrostatic units of potential to volts,

$$e_n = \left[400\pi d\sqrt{\frac{\left(\frac{9\eta}{2}\right)^3}{g\rho}}\right] \cdot \left(\frac{v_u + v_d}{V}\right) \cdot v_d^{\frac{1}{2}} \quad . \quad . \quad \text{(iii)}$$

where $d$ is the distance between the condenser plates and $V$ is the potential in volts applied to them, that is, $E = \frac{V}{300d}$.

Millikan found that consistent results were not obtained with different drops unless they were falling with the same velocities. This he attributed to a failure of Stokes' law to apply to small drops of the size he was observing. The velocity of fall of very small drops was greater than that predicted by the law, a discrepancy which might be due to inhomogeneities in the medium through which the drops were falling. When the spaces between gas molecules, that is, the mean free paths, become comparable in size with the diameter of a drop, the fall of a drop becomes freer and faster than when it is making its way downwards through a throng of closely packed particles, which is the condition assumed in the uncorrected form of the law. Millikan concluded that the velocity of fall must depend upon the pressure of the gas, as well as on the size of the drop and he introduced a factor $\left(1 + \frac{b}{pa_1}\right)$ to give the observed velocity. $b$ is a constant, which he determined with great care. Its value to-day is given as 0·000617. $p$ is the pressure of the air in the cell in cm. of mercury and $a_1$ is the corrected radius of the drop, which can be found with sufficient accuracy from the uncorrected expression for Stokes' law from observations on the rate of fall of the drop in the absence of the electric field, thus

$$a_1 = \sqrt{\frac{9\eta v_d}{2g\rho}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(iv)}$$

Since the velocity occurs to the $\frac{3}{2}$ power in the expression for $e$, the corrected value of unit charge, we have

$$e = \frac{e_1}{\left(1 + \frac{b}{pa_1}\right)^{\frac{3}{2}}}$$

where $e_1$ is the uncorrected value, and the expression for $e_n$ may be written in the form

$$e_n = \underbrace{\left[400\pi d \,.\, \sqrt{\frac{\left(\frac{9\eta}{2}\right)^3}{g\rho}}\right]}_{k_1} \,.\, \underbrace{\left(1 + \frac{b}{pa_1}\right)^{-\frac{3}{2}}}_{k_2} \,.\, \left(\frac{v_d + v_u}{V}\right) \,.\, v_d^{\frac{1}{2}}.$$

*Apparatus constant. Drop constant.*

The quantity in the square bracket may be called the apparatus constant and the term containing $a_1$ may be called the drop constant.

Hence $$e_n = k_1 \,.\, k_2 \,.\, \left(\frac{v_d + v_u}{V}\right) \,.\, v_d^{\frac{1}{2}},$$

$k_1$ is computed for a particular apparatus and a table of values of $k_2$ for different times of fall of drops can be constructed, thus saving time in obtaining values for $e_n$. With

| Time in secs. for falling 20 divisions | Velocity of fall in cm. per sec. = $v_d$ | $v_d^{\frac{1}{2}}$ | $a_1 = k_a \,.\, v_d^{\frac{1}{2}}$ ($k_a$ = 0·0097) | $k_2 = \left(1 + \frac{b}{pa_1}\right)^{-\frac{3}{2}}$ $p$ = 76 cms. |
|---|---|---|---|---|
| 20 | 0·00765 | 0·0875 | 0·000848 | 0·9859 |
| 21 | 0·0073 | 0·0854 | 0·000828 | 0·9855 |
| 22 | 0·0070 | 0·0837 | 0·000812 | 0·9852 |
| 23 | 0·00665 | 0·0815 | 0·000790 | 0·9848 |
| 24 | 0·0064 | 0·0800 | 0·000776 | 0·9845 |
| 25 | 0·0061 | 0·0781 | 0·000757 | 0·9842 |
| 26 | 0·0059 | 0·0768 | 0·000744 | 0·9839 |
| 27 | 0·0057 | 0·0755 | 0·000732 | 0·9836 |
| 28 | 0·0055 | 0·0742 | 0·000720 | 0·9833 |
| 29 | 0·0053 | 0·0728 | 0·000706 | 0·9830 |
| 30 | 0·0051 | 0·0714 | 0·000693 | 0·9827 |

the author's apparatus the movement of a drop over twenty eyepiece divisions is usually timed, and since 13·5 eyepiece divisions are equivalent to 1·0 mm. at a certain telescope setting, which of course must not be changed during the taking of a set of readings, except by the very small amount needed to keep a drop in sharp focus, twenty divisions of the eyepiece scale represent a movement of the drop of 0·153 cm. A portion of a convenient table is given on p. 77.

$$a_1 = \sqrt{\frac{9\eta v_d}{2g\rho}},$$

$\eta$ = viscosity of air at 23° C. (0·000183 gm./cm. sec.).

$g$ = 981 cm./sec.$^2$.

$\rho$ = density of the oil $\simeq$ 0·90 gm./cm.$^3$.

$b$ = 0·000617 (Millikan).

Some typical results obtained with the apparatus described are given below :

I. Time for falling twenty divs. = 32·4 sec.
Time for rising twenty divs. = 82·0 sec.
$V = 120$ volts.
$v_d = 0{\cdot}0047$ cm./sec. ; $v_u = 0{\cdot}00186$ cm./sec.
$v_d + v_u = 0{\cdot}00656$ cm./sec.

$$e_n = 0{\cdot}000396 \times 0{\cdot}980 \times \frac{0{\cdot}00656}{120} \times 0{\cdot}069$$
$$= 14{\cdot}90 \times 10^{-10} \text{ e.s.u.}$$
$$n = \frac{14{\cdot}90}{4{\cdot}8} \simeq 3 \text{ charges.}$$

II. Time for falling twenty divs. = 50·8 sec.
Time for rising twenty divs. = 38·6 sec.
$V = 43$ volts.
$v_d = 0{\cdot}003$ cm./sec. ; $v_u = 0{\cdot}004$ cm./sec.
$v_d + v_u = 0{\cdot}007$ cm./sec.

$e_n = 0{\cdot}000396 \times 0{\cdot}977 \times \frac{0{\cdot}007}{43} \times$ 0·[illegible]54

$$= 34 \times 10^{-10} \text{ e.s.u.}$$
$$n = \frac{34}{4{\cdot}8} \simeq 7 \text{ charges.}$$

It must not be expected that the crude apparatus described here can do more than illustrate the principles involved in this most important physical measurement. The charges on the drops will be found only approximately to be small integral multiples of the unit charge, $4{\cdot}802 \times 10^{-10}$ e.s.u. Nevertheless, in Millikan's hands the apparatus yielded the most precise results and left no room for doubt that charges less than this unit are not encountered in any of the ionization processes he was employing. He did not rely on the process of atomization for the charges on his drops. He irradiated the drops with X-rays and found that charges were picked up, sometimes one unit of charge at a time, sometimes integral multiples of the unit charge. He varied the circumstances of the experiment widely by altering the pressure in the cell, by using drops of oil, glycerine and mercury, and he produced his ions by means of X-rays, ultraviolet light and radioactive substances. In all cases the charges were integral multiples of the unit charge and no smaller charge than this unit was ever found. His values for $e$ are not averages. The experimental arrangements make it possible to measure a single charge. No better evidence of the atomicity of electricity is forthcoming and this precise evaluation of $e$ makes it at once possible to calculate Avogadro's number from the established value for the Faraday of electricity.

$$\begin{aligned} N &= \frac{F}{e} \\ &= \frac{2{\cdot}8922 \times 10^{14} \text{ e.s.u.}}{4{\cdot}8023 \times 10^{-10} \text{ e.s.u.}} \\ &= 6{\cdot}0226 \times 10^{23} \text{ particles per gram molecule.} \end{aligned}$$

These figures are taken from the *Tables of Physical and Chemical Constants*, by Kaye and Laby (Tenth Edition).

Millikan's work in measuring the charge of a unit electrical particle is usually considered to be convincing evidence of the discontinuity of electricity. It is, of course, not direct evidence. A number of inferences have to be made from observations of the movements of drops of oil, which are not themselves perceived by the unaided sight, but are inferred to be present in the apparatus. What is seen in the short range telescope is a point of light scattered or reflected from what is believed to be an exceedingly small drop of oil. In the apparatus described above the drops appear as discs and are presumably seen by reflected light, which is the usual way in which we know of the presence of objects which are not self-luminous. There seems to be no doubt of the existence of the drops. It is from the measurements of their movements that the more impalpable inferences have to be made. In Millikan's experiment observations were made of changes in speed of the drops when they were irradiated with X-rays, from which it was deduced that the changes in speed were always due to the addition or the neutralization of integral multiples of a unit amount of electricity. Many inferences are involved in this conclusion, such as those that have been drawn from observations of the behaviour of charged bodies in an electric field and of the interaction of X-rays with matter, but all have been tested repeatedly by independent observers and have been shown to possess high probability. There are no known weak links in the chain of inferences and it is unlikely that in so important an argument any major sources of error would have been overlooked It may be said that this experiment establishes the discontinuity of electricity with a degree of probability that amounts to certainty for many practical purposes.

# CHAPTER VIII

# RADIOACTIVITY

In 1896 Henri Becquerel in Paris was experimenting to find out whether the light from substances which shine in the dark, such as were used for making luminous paint, might not be composite and consist in part of penetrating rays like X-rays, which had been discovered the year before. He happened to use a preparation of uranium as his luminous substance and found that it did indeed affect a photographic plate, although the plate was wrapped in black paper. The effect was proved to be nothing to do with visible light. It was a property of the element uranium and its compounds, all of which emit rays like X-rays. The same property was found to belong to thorium and its compounds, although in both cases the effect is so weak that it had been overlooked. Such substances are said to be radioactive. In all over thirty naturally occurring radioactive elements were discovered, but many of these are isotopes and all are derived by radioactive transformations from the two parent elements thorium and uranium. Perhaps the most important of the radio-elements is radium, which has an activity about a million times as great as that of uranium, its parent.

The radiation given by a thorium or uranium mineral is composite, consisting of $\alpha$-rays, $\beta$-rays and $\gamma$-rays. $\alpha$-rays were shown to be streams of particles, travelling at high speeds, but stopped by a few centimetres of air at S.T.P., or by a fraction of a centimetre of solid matter. If $\alpha$-rays are collected in an exhausted vessel the spectrum of helium can be obtained and since each particle can be shown to possess two positive charges, they are regarded as helium nuclei, that is, as helium atoms from which two planetary electrons have been lost. They are now called $\alpha$-particles.

$\beta$-rays possess a negative charge and travel nearly as fast as light. They are electrons and are more penetrating than $\alpha$-particles.

$\gamma$-rays are electromagnetic waves of very short wavelength and penetrate several centimetres of solid matter.

All these types of radiation cause the ionization of gases through which they pass, a fact which provides a simple means of detecting and measuring them. $\alpha$-particles give scintillations when they fall upon suitable substances, such as willemite or Sidot's blende. They give dense straight tracks when they ionize air which is supersaturated with water vapour, a fact upon which many designs of cloud chamber depend and from which much information has been gained. They also give conspicuous tracks in special photographic plates.

The presence of $\beta$-rays is shown by their ionization of air when $\alpha$-particles have been cut off with screens and similarly $\gamma$-rays can be detected when both $\alpha$-particles and $\beta$-rays have been cut off. It is not so easy to demonstrate the presence of $\beta$-rays in the cloud chamber, nor by means of photographic plates, as it is that of $\alpha$-particles.

The counting of scintillations was put to good use by Rutherford in providing yet another value for Avogadro's number $N$, but it was by the skilful use of the electrometer that the early workers disentangled the complicated relations that exist among the radioactive elements.

*Avogadro's Number from Counts of $\alpha$-particles.* By counting the number of $\alpha$-particles emitted per second by a radioactive source and also measuring their charge a method of estimating $N$ has been developed which is entirely independent of the kinetic theory of gases. The first count was undertaken in 1905 by Rutherford, but he had to rely on the accepted value for $e$ in order to compute the number of particles. In 1908 direct counts of the scintillations produced by $\alpha$-particles upon phosphorescent screens were made and, in another method, the number of particles entering a Geiger counter was observed together with the total charge due to them. Many later determinations have been made with improved accuracy ; in fact, the results obtained serve as a check on the accepted value of $e$. Modern work gives a count of about $3{\cdot}72 \times 10^{10}$ $\alpha$-particles per second per gram of radium freed from its disintegration products.

The law of radioactive disintegration may be stated in the form :

$$n = -\frac{dn}{dt} \cdot \frac{1}{\lambda}$$

where $n$ is the number of radioactive atoms remaining at a given time $t$ and $\lambda$ is the radioactive constant. For 1 gm. of radium it is found that $\frac{dn}{dt} = -\,3{\cdot}72 \times 10^{10}$ particles per sec. If $T$ is the half-life period,

$$\begin{aligned}\frac{1}{\lambda} = \frac{T}{\log_e 2} &= \frac{1580 \text{ years}}{0{\cdot}693}\\ &= \frac{1580 \times 365 \times 86400}{0{\cdot}693} \text{ sec.}\\ &= 7{\cdot}18 \times 10^{10} \text{ sec.}\end{aligned}$$

The atomic weight of radium is about 226 ; hence $N$, the number of atoms in a gram atom of radium

$$\begin{aligned}&= 7{\cdot}18 \times 10^{10} \times 3{\cdot}72 \times 10^{10} \times 226\\ &= 6{\cdot}05 \times 10^{23}.\end{aligned}$$

This is Avogadro's number and is in good agreement with the value obtained from kinetic theory and from measurements of $e$.

### (1) RELATIVE RADIOACTIVITY OF MINERALS

The relative activity of radioactive minerals can be demonstrated to a large audience by means of a projection type electroscope. A square brass box is constructed with its top and one side removable, so that adjustments can be made to the needle. Glass windows in two opposite sides are off-set to the side on which the needle is to move, their size being kept to a minimum to reduce the area over which static charges may occur. The usual design for an $\alpha$- or $\beta$-ray electroscope is followed in providing a drawer below the electroscope chamber by means of which the substances to be tested can be introduced. A circular brass disc electrode serves to collect the charge. This is supported by a brass rod passing through the floor of the electroscope, but is insulated from it by a cylinder of polystyrene or some other insulating substance of good surface resistivity. The brass rod protrudes 1 cm. or so into the electroscope chamber and a short brass tube surmounted by a flat strip of brass supports the needle. A very sharp optical image of the needle can be obtained if a suitably fine pointer is employed. Fine glass needles can easily be made by pulling out hot glass tubing, the needle being made to conduct by dipping it in Indian ink. This needle is attached to its support by a small hinge of gold leaf, which need not be more than 1 × 4 mm. in size. The method of mounting the needle is simple. The gold leaf is cut between the tissue paper in which it is supplied and is manœuvred to the edge of a glass plate. The end of the needle is lightly smeared with a solution of orange shellac in alcohol and is immediately but very carefully brought into contact with the gold leaf, the glass tube of the needle extending nearly half-way along the axis of the gold leaf strip. The brass support is similarly smeared with the alcoholic shellac and is brought into contact with the free part of the gold leaf strip, so that when the whole is lifted the gold leaf will fold over and form a hinge :

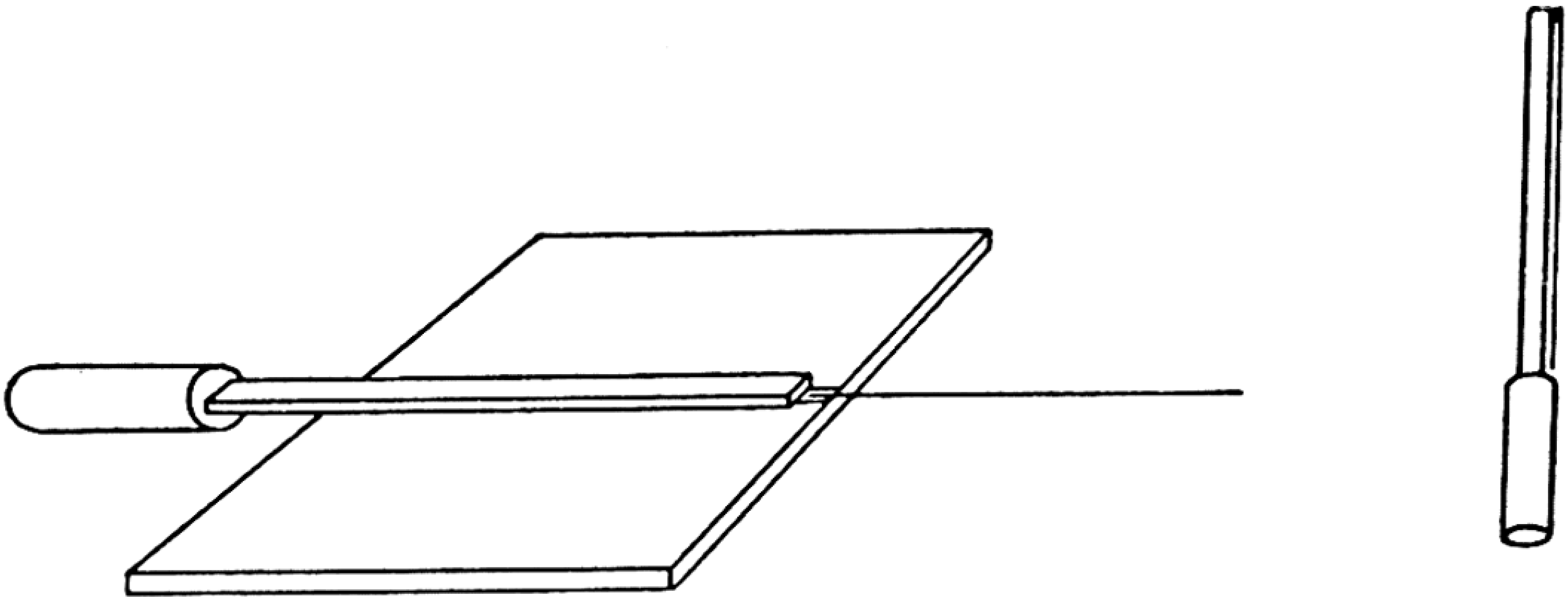


FIG. 39. Method of attaching capillary glass electrometer needle by means of gold-leaf hinge.

The needle is now ready for insertion in the electroscope, which may be charged by bringing a charged body into contact with the electrode inside the drawer.

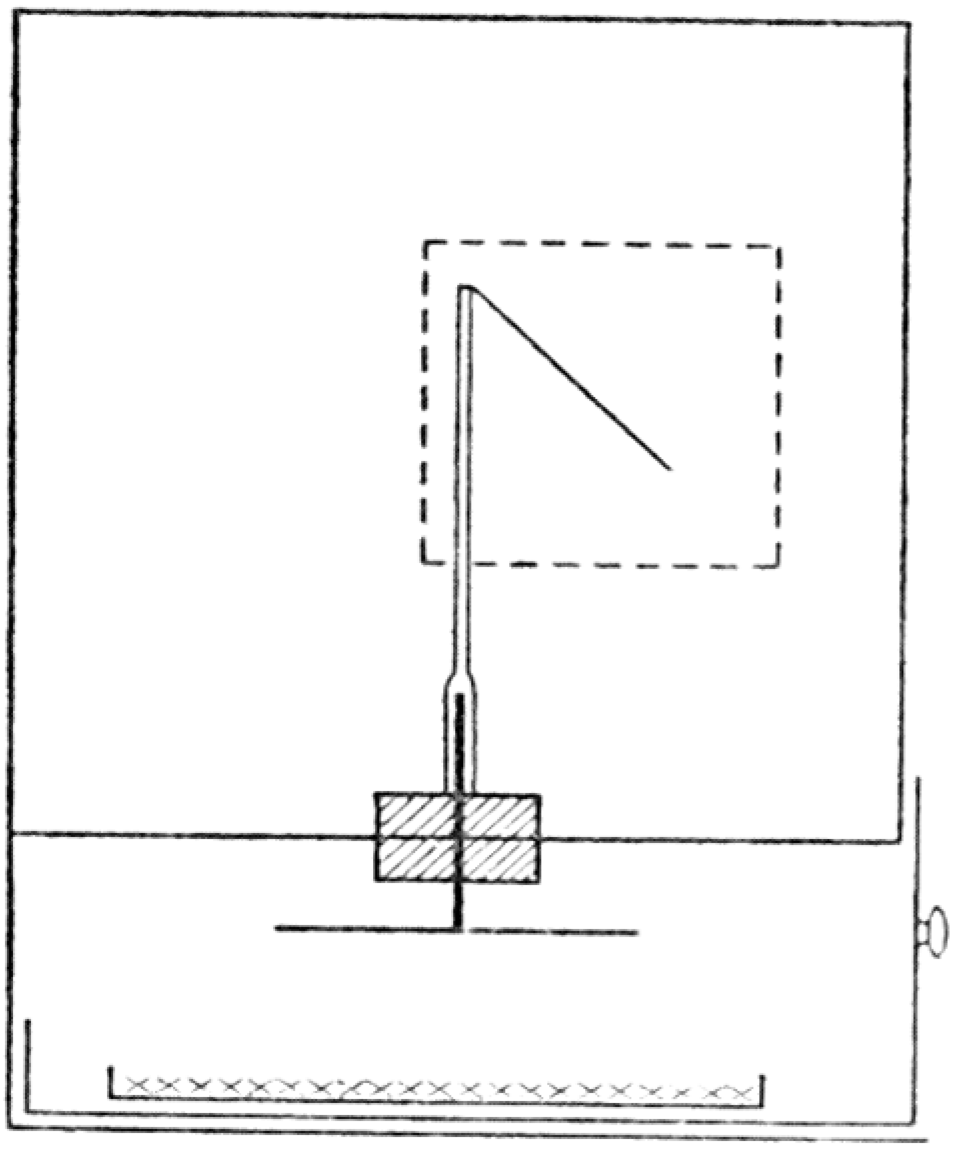


FIG. 40. Section of projection type electroscope for comparing radioactivity of minerals.

The electroscope is mounted in a suitable projection lantern and a sharp image of the needle is obtained on the screen. It is relatively simple to make such a projection lantern, if the need should arise, provided a pair of condensing lenses and a projection lens are available. The source of light may be a 24- 36- or 48-watt motorcar headlamp bulb. Among other suitable lamps there is a G.E.C. 108-watt tungsten strip lamp, which requires 18 amps. at 6 volts, or a Siemens 150-watt compact source filament lamp taking 12 amps. at 12 volts. The second of these is very bright. A pointolite lamp is also very good if direct current is available. The lamp housing and condenser are mounted on a support so as to leave a free space of 10–12 inches between the condenser and the projection lens. Both may be carried on a rigid side bar, as shown in Fig. 41.

The method of measuring the activity of the radioactive substances is to time the fall of the needle over a certain number of divisions on a scale. As this scale cannot be placed inside the electroscope, it may be painted on the screen on which the image of the needle is to be received. A large sheet of cardboard or, better, of plywood, is very suitable if painted white. The position of screen and lantern must be noted. The electroscope is charged and the movement of the needle is recorded on the screen by means of a series of pencil marks during the natural leak of the instrument or, if this is too slow, during the movement produced by some radioactive material. The path of the pointer is then painted in and suitable arbitrary divisions are marked and numbered.

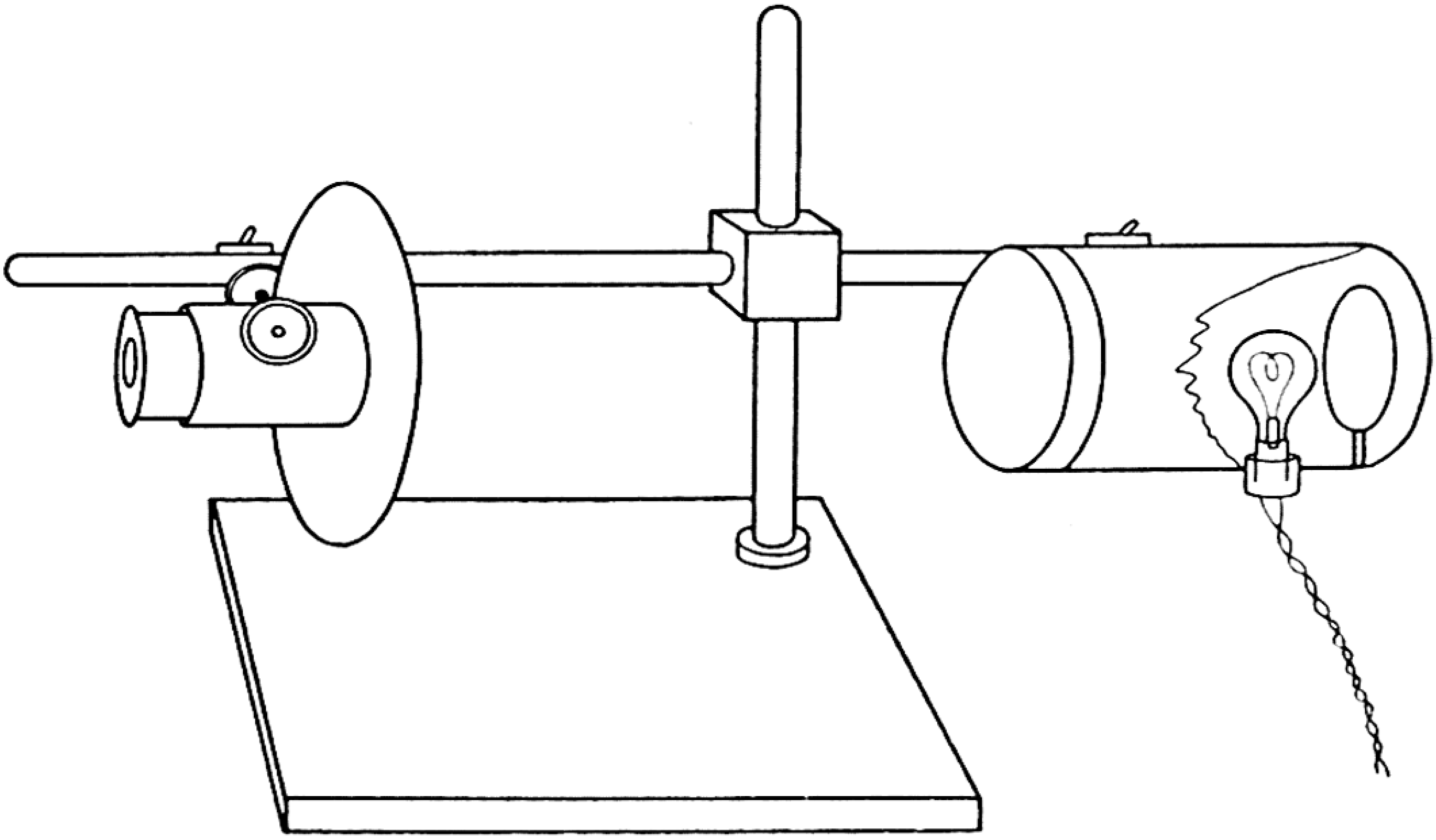


FIG. 41. A form of lantern for use with the projection electroscope and other bulky pieces of apparatus.

To use this apparatus for a lecture demonstration, the natural leak of the electroscope must be found over the range of scale divisions which it has been decided to use for the subsequent measurements. This should be done just before the demonstration, as the rate of leak will depend upon atmospheric conditions. As the room will probably be darkened for the demonstration and as the attention of the audience may be expected to be concentrated on the screen, the timing is best carried out by means of a metronome, the counting of whose beats will not interfere with watching the movement of the image of the electroscope needle. All the members of the audience will be able to take part in making the measurements of time, which, if the movement of the needle is taken over the same divisions of the scale on each occasion, will be inversely proportional to the activity of the radioactive substances, after allowing for the natural leak. The following results are typical. The radioactive substances were placed in powdered form on metal trays of the same area in the drawer in the electroscope. The movement of the needle is always timed to start from the same scale division. The natural leak was two scale divisions per minute.

| *Radioactive substance* | *Time of fall of needle over* 10 *divisions* |
|---|---|
| Monazite | 64 sec. |
| Thorianite | 6·5 sec. |
| $Na_2U_2O_7$ | 20 sec. |
| $U_3O_8$ | 23 sec. |
| Uranite | 8·5 sec. |
| $ThO_2$ | 6·0 sec. |

### (2) A MODEL SPINTHARISCOPE

An instructive model experiment which provides an analogy between one of the effects of radioactive disintegration and a well known large-scale phenomenon can easily be performed. A stream of solid particles is directed at a phosphorescent screen and the flashes of light produced by the separate impacts are observed. It is well known that certain specimens of slightly impure zinc sulphide give a flash of light when the crystals are crushed or are scratched with a needle. This substance is used for making phosphorescent screens. The apparatus consists of a light-tight box in one side of which is a circular opening about 2 cm. in diameter covered by a sheet of glass upon which a layer of phosphorescent zinc sulphide with short afterglow has been deposited. The phosphor may be suspended in some volatile organic liquid such as acetone, together with a binder, sprayed upon the glass plate and dried. The screen is observed by means of a lens of about 10 cm. focal length. On the side of the box opposite to the phosphorescent screen a tube is fixed through which a stream of dry sand can be blown. When the eye is sensitized by being kept in darkness for about five minutes the sand stream is started and the phosphorescent screen is observed through the lens. As each particle of sand strikes the phosphor a short-lived flash of light is seen, the whole effect being that of a circle of random flashes continuing as long as the stream of sand is allowed to play upon the glass plate. A convenient arrangement for producing the stream of sand particles is shown in Fig. 42.

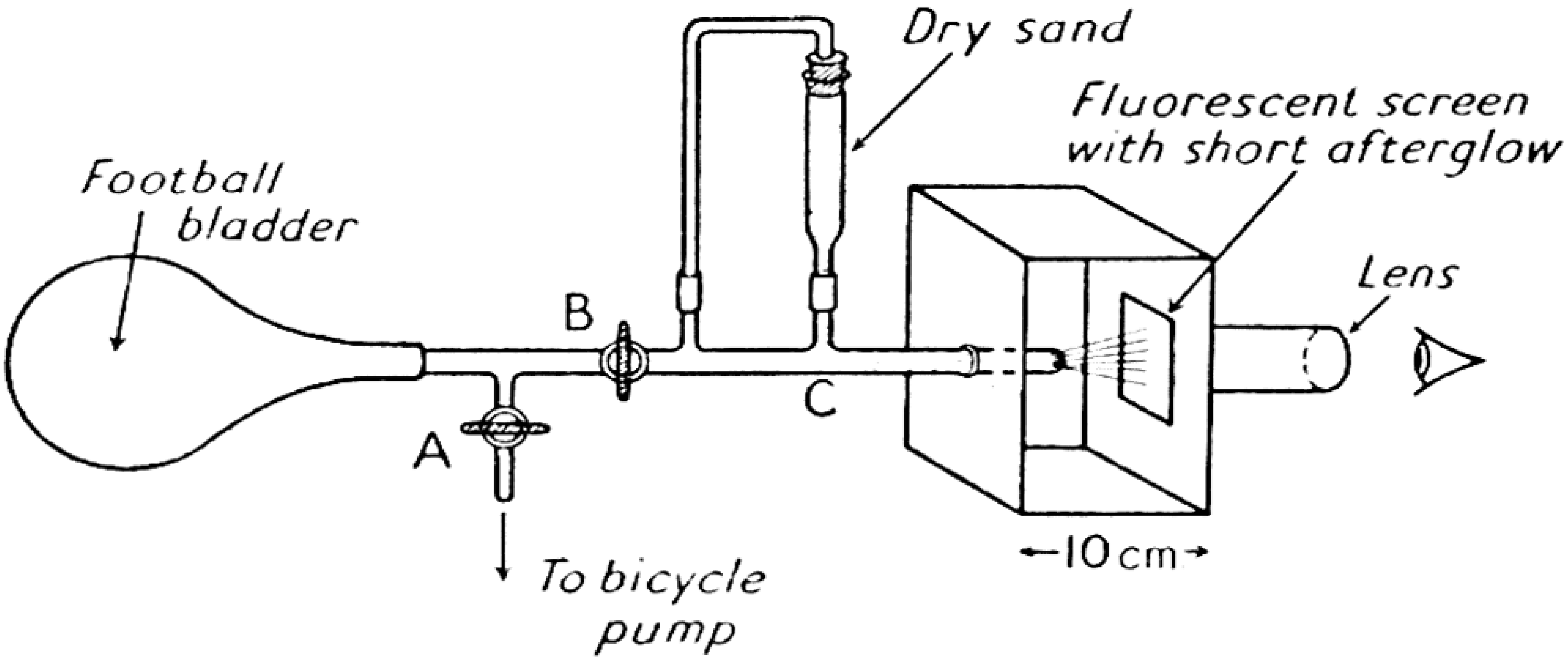


FIG. 42. Model spinthariscope. A stream of sand grains is blown by a current of air on to a fluorescent screen. The flashes are observed through a lens.

A football bladder is inflated by means of a bicycle pump through the tap *A*, which is then closed. Dried sand which has been sifted to remove coarse particles is contained in the reservoir and the pressure equalizing device ensures that the sand will fall under gravity when the tap *B* is opened. The T-joint at *C* is of 1·5 mm. bore capillary glass tubing and does not become choked if the sand is dry. The sand blast soon removes the phosphor from the part of the glass plate where it strikes, a fresh portion of the plate being used for each demonstration. The instrument is a model spinthariscope and shows how flashes of light may be produced by the impact of a stream of particles.

When a radioactive preparation is held at a suitable distance from a similar screen, which is observed through a magnifying lens by a dark-adapted eye, a similar appearance is seen. It is as though the phosphorescent screen is being continuously bombarded by a random stream of particles and this is indeed the explanation put forward to account for the radioactive phenomenon. The gross particles of sand produce flashes of light as long as the stream continues, but the radioactive substance sends out its stream of particles for days, months or years, according to its nature. The model experiment described above does not prove that the flashes in the spinthariscope are due to particles of matter rather than to continuous waves, but it renders the explanation in terms of particles plausible, by showing that a comparable phenomenon can be displayed with objects on a scale with which we are familiar.

The view that the flashes of light from radioactive substances are due to particles and not to waves is reinforced by an early experiment described by Soddy. A polonium source is placed on a flat plate 1 or 2 cm. in diameter in the centre of a 2-litre flask, half of whose inner surface has been covered with a layer of a fluorescent substance with short afterglow. Nothing is visible when the air is at atmospheric pressure, for the radius of the flask is greater than the range of the $\alpha$-particles, but if the flask is connected to an air pump and the air is withdrawn, the half of the flask which is coated becomes suddenly luminous. This demonstration should be performed in a darkened lecture theatre and is very striking, especially in support of the view that the range of the $\alpha$-particles has increased owing to the removal of the obstructing air molecules. No explanation of this effect is forthcoming on the hypothesis of the emission of continuous waves.

Some of the most convincing experiments that can be performed in an attempt to demonstrate the existence of the particles given out in radioactive disintegrations are those made with the Wilson cloud chamber. The condensation trails left by high-flying aircraft in certain atmospheric conditions are familiar to all. That the trails are produced by the passage of an aeroplane through the air and that they consist of condensed water vapour are common knowledge. By analogy, it may be assumed that the condensation trails produced in a specially prepared cloud chamber by the presence of a radioactive substance are due to the passage of particles emitted at high speed by the radioactive body. The analogy mentioned above is not put forward as a proof of the existence of the particles, which are themselves invisible. In the case of the aeroplane, a pair of field glasses may be enough to make the object visible which is producing the condensation. No optical instrument can give a visible image of an $\alpha$-particle in the cloud chamber, but the tell-tale condensation trail may be taken as strong presumptive evidence of the existence of a moving particle. The analogy must not be pressed too far, as the process of condensation may be different in the two cases.

Many forms of cloud chamber have been devised and all students of science should be given the opportunity to witness the phenomena that they show. The well known wheel-operated chamber of Shimizu is somewhat expensive and many teachers would prefer to make an apparatus to their own design. The simple form of cloud chamber described by R. S. Clay on page 280 of No. 74 of the *School Science Review* works very well in the form modified by W. Llowarch, but if used with thorium C it requires a period of preparation and has only a short working life unless the radioactive source is renewed. Llowarch's account is to be found on page 107 of No. 113 of the *School Science Review*. If any radium salt is available, sufficient of it to show the tracks of $\alpha$-particles can be made to adhere to the head of a pin by merely touching the salt with it, especially if the pin has recently been dipped in a solution of shellac in alcohol. Such a source will not need renewing.

### (3) PROJECTION TYPE CLOUD CHAMBERS

The problem of projecting an image of the tracks on a screen so as to be visible to large audiences has been solved and, if a little trouble is taken in the construction of the apparatus, most satisfactory results can be obtained. The form of cloud chamber to be described first was the property of Professor E. N. da C. Andrade and was made by Mr. S. Walden for him.

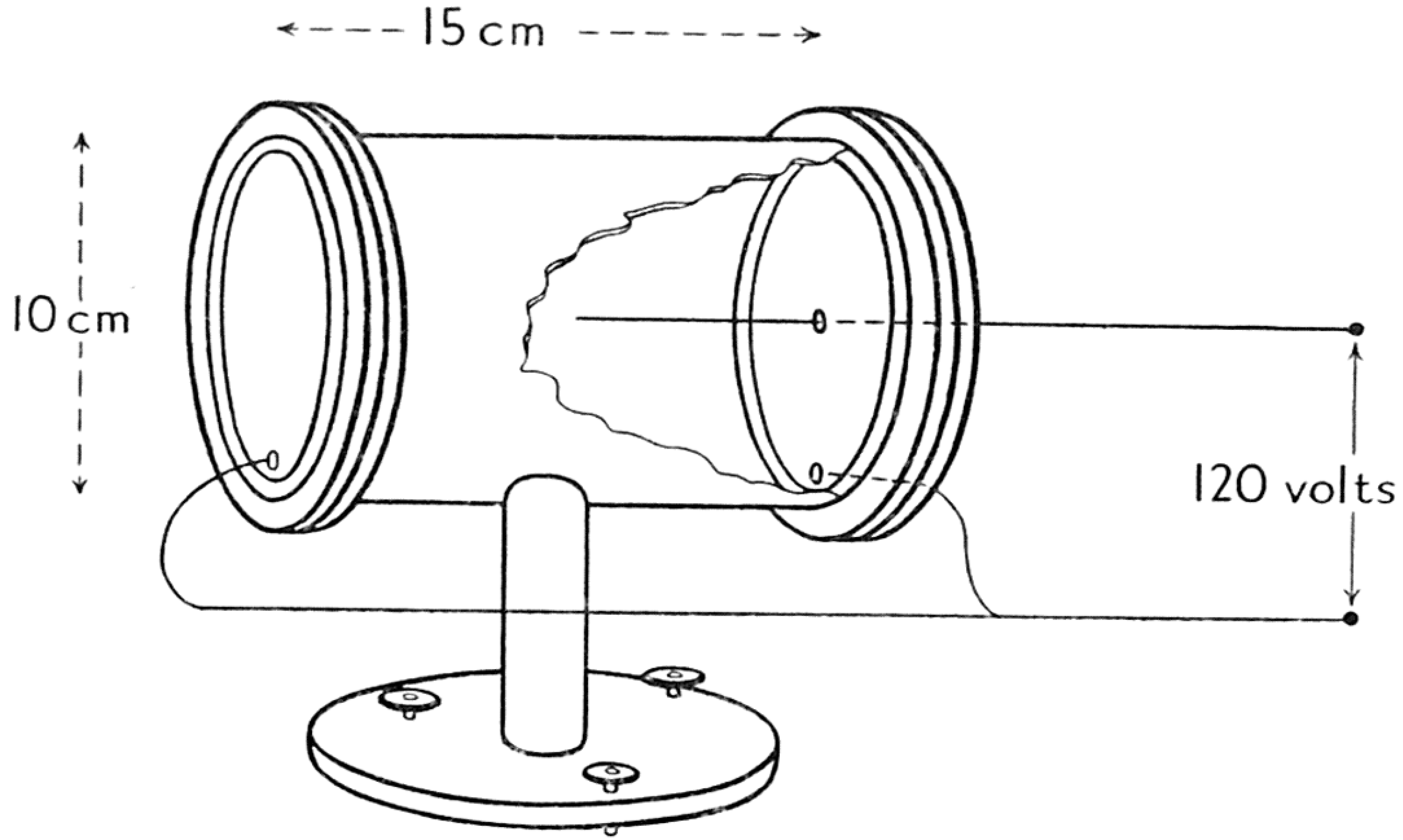


FIG. 43. Professor Andrade's projection type cloud chamber. The radioactive substance is placed on the tip of the axial wire. The lantern shown in Fig. 41 may be used for a lecture demonstration.

The author was allowed to see this instrument after it had suffered bomb damage at University College, London ; he had one made which works on the same principle. A photograph of tracks produced by a weak radium source with this instrument is shown in Plate III A, facing page 104.

The diameter of the field of view is limited by the size of the condensing lenses in the projection lantern used. Lenses which are 4 inches in diameter will allow of the projection of those α-particles from radium whose range in air at atmospheric pressure is less than 5 cm. The chamber consists of a brass cylinder 6 inches in diameter and 6 inches long (Fig. 43). A soft rubber sleeve fits inside it and the cylinder is closed at the ends by glass plates in such a way as to make the interior of the cylinder gas tight. A tube passes into the cylinder somewhere on its middle circumference and a circumferential groove is cut inside it to allow the rapid escape of air from between the rubber sleeve and the brass. A bicycle pump and a quick release valve are connected by strong rubber tubing to the metal tube on the cylinder. When air is pumped into the space between the rubber sleeve and the brass cylinder, the volume of the air in the chamber is decreased by an easily controllable amount, the rubber sleeve taking up a curious segmented conformation depending on its dimensions, tension and elasticity. When the release valve is operated the compressed air in the annular space between the rubber and the brass cylinders is rapidly expelled by the elastic recovery of the rubber sleeve and the air in the chamber undergoes adiabatic expansion, with consequent cooling. If a radioactive source is placed on the end of a wire passing half-way along the axis of the cylinder, the radial expansion of the air is sufficiently free from eddies to allow of the production of tracks in all directions from the source. Those in the optical plane of projection give good images on the screen or may be photographed as described below.

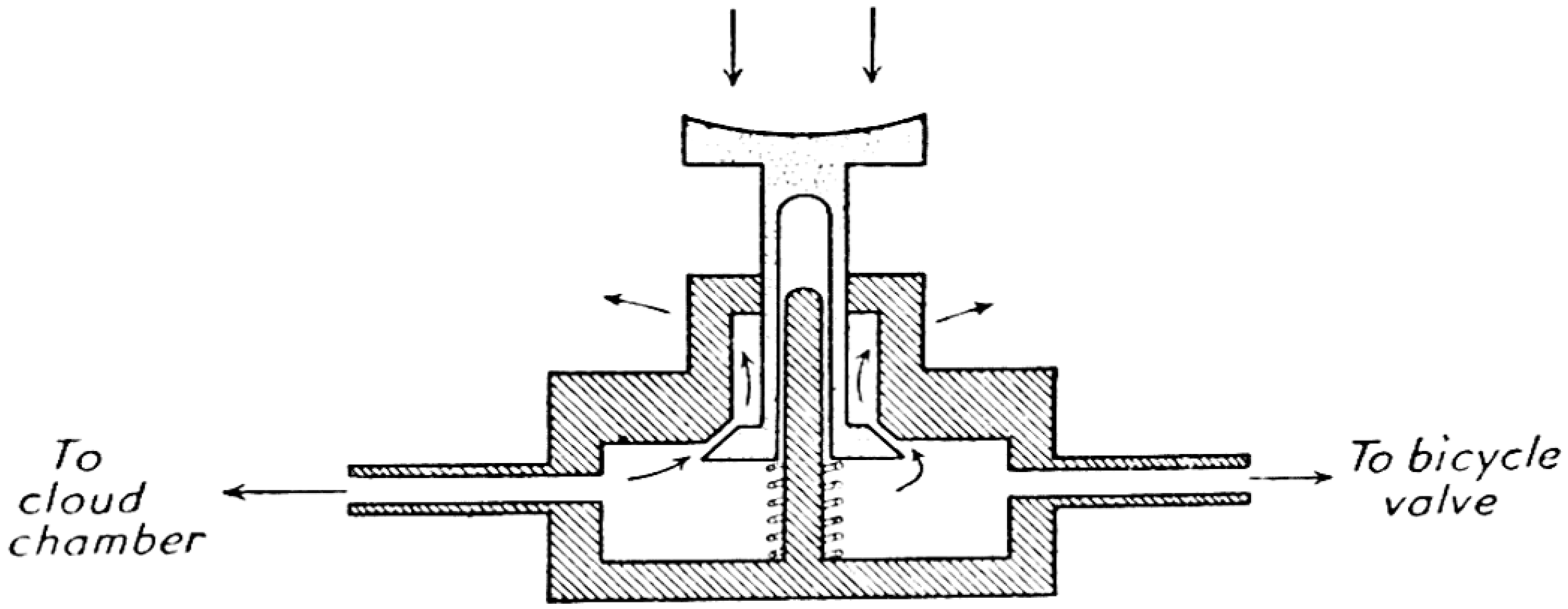


FIG. 44. Section through release valve.

The release valve is a rectangular block of brass drilled axially along its greatest length. It is also drilled at right angles to this direction to admit a poppet valve which is seated by a strong spring. A bicycle valve is soldered on at one end and a tube to take the rubber connection to the cloud chamber is soldered at the other end. The poppet valve is operated by a push button and gives ample clearance for the exhaustion of the compressed air.

The removal of ions from the chamber is carried out by means of two ring-shaped electrodes of tin-foil adhering to the inner surfaces of the glass plates. The glass is drilled to make connection to these electrodes. They are connected together and to one pole of a 120- or 240-volt dry battery, the other pole of which is connected by a thin copper wire to the outside end of the nickel wire carrying the radioactive substance. This may be a speck of a radium salt, a deposit of polonium, or thorium C. One glass end plate is drilled in the centre to carry a small brass bush which is cemented gas-tight to the glass. The nickel wire is soldered axially to a brass screw which fits into this bush, the joint being made gas-tight with a small rubber washer, as shown in Fig. 45.

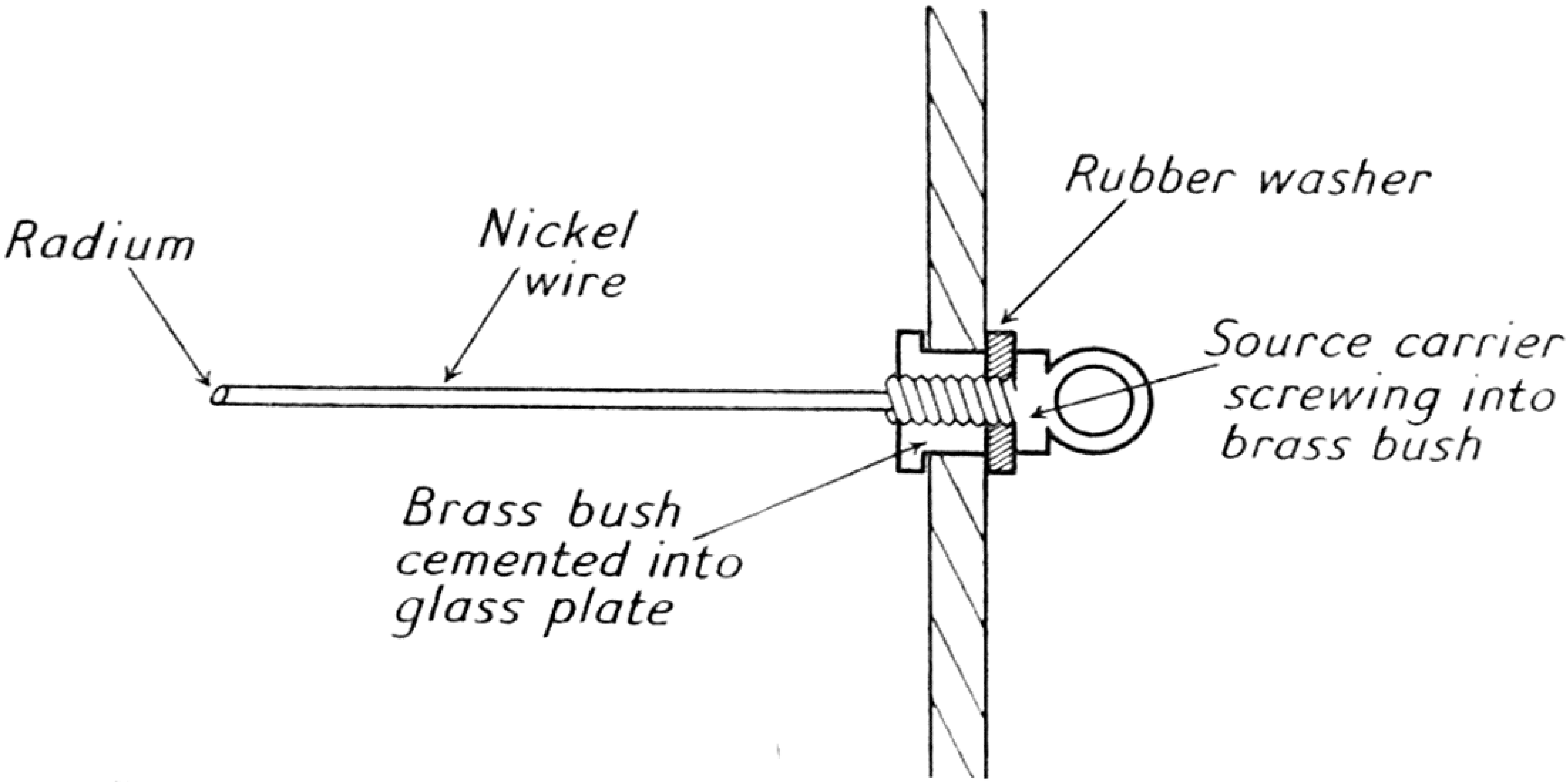

Radium
Nickel wire
Rubber washer
Source carrier screwing into brass bush
Brass bush cemented into glass plate

FIG. 45. Source carrier for Andrade's projection type cloud chamber.

A blurred image of the brass bush appears in the centre of the field of view, but it serves the useful purpose of indicating the point from which the audience may expect to see the α-particle tracks when the valve is opened.

Various recommendations have been made for increasing the sensitivity of the chamber. The amount of pumping required to give good results must be found by trial and is somewhat critical. The author has used a drop or two of propyl alcohol in the chamber instead of water with very satisfactory results and has also mixed a few c.c. of argon with the air, but it is not thought that these refinements are essential. The best results are obtained by keeping the electric field on continuously and by allowing about twenty seconds for the air in the chamber to cool after pumping before the pressure is released. The tracks are very slender and sharp, as can be seen from the photograph. They last for a few tenths of a second.

For the purpose of projection special lantern arrangements are required to allow the cloud chamber to be brought up close to the condensing lenses. The projection lens may then have to be supported in a separate carrier, but most laboratory lanterns can easily be adapted for the purpose.

The tracks can be photographed very simply. A quarter plate camera is used with the lens removed, the distance being adjusted so that the circular image of the cloud chamber nearly covers the area of the plate. A few trials may be required to ensure that a sharp image is received on the ground glass screen before a plate is inserted. The shutter of the camera should have a remote control, the operator releasing first the valve of the cloud chamber and the shutter of the camera immediately afterwards. The necessary time interval is not difficult to estimate, but it must not be expected that every exposure will be perfect. With Kodak P 1200 plates and a shutter speed of $\frac{1}{50}$th of a second, good photographs capable of enlargement have been obtained. The stop should be kept open.

Another cloud chamber suitable for projection of the tracks has also been constructed. It was devised by C. T. R. Wilson and J. G. Wilson and is described briefly by Morgan and Burstall in their *Inorganic Chemistry*, published by Heffer & Sons Ltd. in 1936. The apparatus is in two parts. The compression of the air is carried out in the lower part, which consists of a short brass cylinder closed at one end by a brass plate and at the other end by a diaphragm of sheet rubber. Air is pumped in between this diaphragm and another brass plate, the dimensions being so chosen that an expansion ratio of about 1–1·3 is secured when the pressure is released. The cloud chamber, which is a parallel-sided glass cell, is placed on top of the brass cylinder, its special feature being that radial expansion is produced by an annular baffle pierced with many holes. This ring is set eccentrically. The two parts of the apparatus are connected by a wide neck of rectangular section.

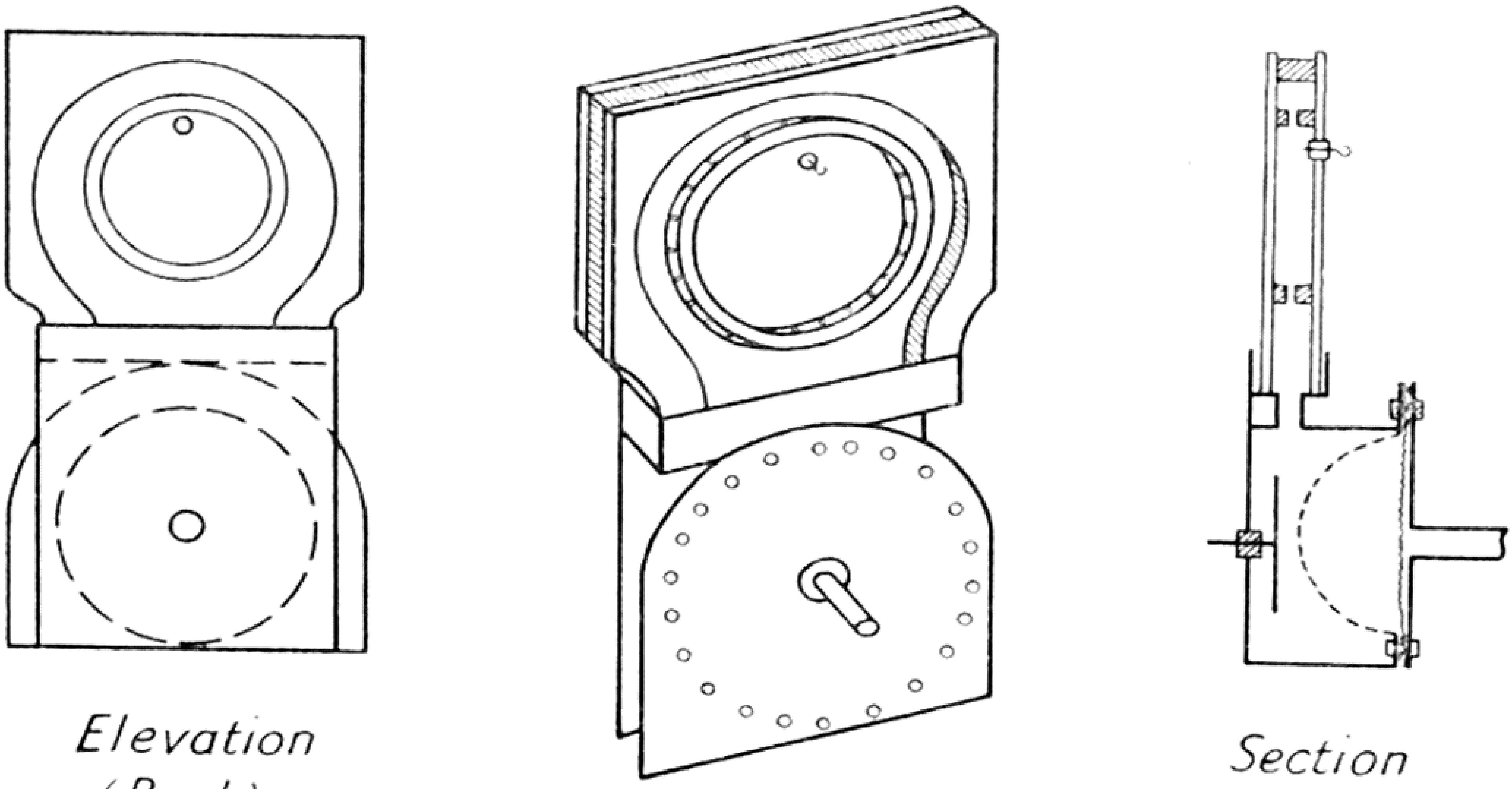


FIG. 46. Projection type cloud chamber devised by C. T. R. Wilson and J. G. Wilson.

The making of a piece of apparatus of this kind is not difficult if machine tools and materials are available, but it often happens that the chemist has to rely on his own skill with hand tools and that his choice of materials is limited by what is readily available. The apparatus to be described was made without the use of machine tools, except that a drilling machine was employed for making the twenty-eight holes required for securing the diaphragm. The figures show the appearance of the instrument and also the back and side elevations :

The lower part of the apparatus consists of a brass cylinder 6 inches in diameter and 2¾ inches in length. It is soldered to a back plate 9 inches × 6½ inches and to a circular ring in front which provides the seating for the rubber diaphragm. This ring is 7½ inches in external and 5½ inches in internal diameter. A circle of red rubber sheet of the kind used for bellows is cut to fit the ring and a D-shaped plate serves both to make an air-tight joint and to provide a secure stand for the apparatus. Twenty-eight holes are cut near the edge to admit short bolts which make the joint air-tight. A rectangular slot is cut in the brass cylinder into which fits a short neck of sheet brass, projecting ¾ inches through the floor of a trough fixed to the back plate. All joints are soldered and must be gas-tight. A flat plate is inserted through an insulating bush in the back plate for removing ions from this part of the apparatus.

The glass cell is fashioned out of two pieces of ¼-inch plate glass, each 8 × 9 inches, a hole being cut in one of them at the appropriate point for the insertion of the radioactive substance. The construction of this source carrier is the same as in Andrade's cloud chamber. The two glass plates are shaped to fit the rectangular trough by carefully breaking away the glass with pliers. The edges of the glass plates should be ground on emery cloth before this process is carried out. A piece of ebonite or other insulating material not less than ½ inch in thickness is made the same size as the glass plates so that the three together will fit into the rectangular trough, giving a gas-tight joint with wax. A circular hole 7 inches in diameter is cut in the ebonite and the lower edge is also removed, leaving a collar-shaped piece which serves to separate the glass plates and to act as the wall of the cloud chamber. A ring of the same ebonite ½ inch wide and 4 inches in internal diameter is cut and is pierced with many radial holes. The surface of this ring is sandpapered to reduce it by the thickness of two sheets of copper foil, from which rings are cut to serve as collecting plates for ions. The copper rings are connected together and a wire is brought from them outside through the ebonite. All these parts are warmed to 60°–70° C. and melted wax is applied to the surfaces of contact, care being taken that the ring with the radial holes is placed eccentrically near the top of the cell. Cramps should be fitted at the four corners until the wax has hardened. The rectangular trough is then warmed and a layer of about $\frac{1}{4}$ inch of Faraday wax or other suitable wax is melted in it. The glass cell is then inserted in the trough and allowed to cool.

It is first necessary to test the cell for gas tightness. This may be done by immersing it in water or by painting all joints with soap solution and increasing the inside pressure by pumping. It is best to keep two cramps on the top corners of the glass plates to prevent failure of the waxed joints. The nickel wire source carrier is then removed and a few drops of propyl alcohol are run in through a fine bore glass tube, such as may be made by drawing out a test tube. A minute speck of a radium salt or other radioactive preparation is then placed on the end of the source carrier, which is firmly screwed home. It is connected to one pole of a 120- or 240-volt dry battery, the other pole of which is connected to the copper rings and to the insulated plate in the brass cylinder. After a few preliminary expansions to remove stray ions and to distribute the alcohol vapour, the chamber may be operated, the same release valve being used as in the apparatus already described. A few trials will show how many strokes of the pump are required to give the best results. This kind of cloud chamber fits a standard lantern more readily than that of Andrade, as the tracks may be formed within 2 cm. of the condensing lenses and the images can easily be shown to large audiences.

This demonstration leaves little room for doubt that invisible particles of limited range are being shot out by the fragment of radioactive material which has been placed on the nickel wire. No alternative explanations have been offered and, although direct evidence of the existence of particles of atomic dimensions again eludes us, the simplicity of the inferences required for drawing the conclusion that we have here a manifestation of the discontinuity of matter is such that no reasonable person will deny it, unless evidence to the contrary is forthcoming at some future time.

### (4) NUCLEAR TRACKS

In recent years it has become possible to produce a permanent record of the tracks made by some of the particles given off in radioactive disintegrations. The manufacture of photographic plates of fine and uniform grain, having a much higher ratio of silver halide to gelatine than is usual in ordinary photographic film, has provided a means of recording the activity of single atoms. The thorium atoms, for instance, in a dilute solution of thorium nitrate will leave a visible record of their disintegration spread at random over the field of view of a microscope. These $\alpha$-particle tracks, as they are thought to be, may be photographed and enlarged to any size.

The technique of this operation is extremely simple and very good results may be obtained nowadays with the nuclear track plates produced by Messrs. Kodak and Messrs. Ilford. By the courtesy of Messrs. Kodak some N.T.2a plates were obtained and the recommended procedure was faithfully carried out. A plate was unwrapped in the dark and placed in a 0·05 per cent. solution of thorium nitrate for ten minutes, emulsion side up. The plate was then taken out of the solution and placed in a cardboard box within another box and left for seven days. Development was carried out in darkness using Kodinol developer, 5 c.c. in 120 c.c. of distilled water. The time of development was twenty minutes. The plate was then washed rapidly with water and placed for five minutes in a stop bath which consisted of a 5 per cent. solution of sodium bisulphite. It was then put in an acid fixing bath for forty-five minutes, washed in running water for fifteen minutes and hardened for fifteen minutes in 10 per cent.

formaldehyde. It was then washed again. Inspection with the microscope using a $\frac{1}{6}$-inch objective and a × 15 eyepiece showed many fine thorium stars, some few of which possessed the maximum number of tracks, namely five. The tracks are attributed to the successive disintegrations of a radiothorium atom, the five α-emitters being radiothorium, thorium X, thoron, thorium A and thorium C′. Occasionally a thorium star is formed in which all the tracks are approximately in the focal plane of the microscope, but as a rule fewer of them than five are focussed sharply at a time and it is necessary to alter the fine adjustment of the microscope to follow a particular track to its end. The separate grains of silver bromide that have been activated by the α-particle can often be distinguished. Great cleanliness during development and care not to over-develop are necessary if the background of unexposed silver grains is to be kept down to a minimum. It is said that this background can sometimes be removed by scraping an unhardened film lightly with a razor blade, as these unwanted silver particles are mostly near the surface, whereas the nuclear tracks are mostly buried in the emulsion. See Plate III, B.

The tracks can be photographed in the usual way. The accompanying picture was taken with a Kodak O–250 lantern plate, using an inexpensive attachable cone camera which fixes to the eyepiece of the microscope. A $\frac{1}{12}$-inch oil immersion objective was used with a × 10 eyepiece. The exposure was thirty-five seconds, the illumination being a 100-watt tungsten lamp placed 6 or 7 cm. from the microscope mirror. The relative lengths of the tracks can be measured, the longest being that due to the α-particle from the short-lived thorium C′, in accordance with the Geiger-Nuttall relation.

Uranium salts give a somewhat similar result, but the pattern of the tracks is different, as the number of disintegrations with two or more branches is very much smaller.

It is claimed that the tracks of electrons of energies less than 100 Kv. can be recorded with these plates, but it has not been found possible to get any indication of the radioactivity of potassium, which is said to possess a radioactive isotope, the $\beta$-emitter $K^{40}$, in the proportion of 1 atom of $K^{40}$ to about 9,000 atoms of $K^{39}$. It is thought that the energies of these $\beta$-particles are too great to be recorded with the emulsion used in N.T.2a plates. Their mean energy is about 0·7 Mev.

Care must be taken at this point to avoid drawing conclusions which are not warranted by the evidence. Each thorium star, it is argued, marks the position of a single thorium atom. The thorium atom, so to speak, leaves its signature in the act of disintegration. The element thorium is therefore present in the form of separate particles. The radiating tracks serve to mark the position of an atom and to provide evidence for its separate existence. The presence of the tracks is in this case ascribed to $\alpha$-particles, and the tendency to-day is to ascribe the formation of tracks in photographic emulsions to moving particles of some kind. Further experimental evidence must be brought forward before it can be concluded that the tracks are produced by the passage through the emulsion of discontinuous particles. In fact a close inspection of the thorium tracks provides circumstantial evidence of the kind required. A good many of the tracks can be seen on enlargement to be made up of separate silver grains. There are often spaces between these grains near the source of the tracks, but the silver grains are close together or even apparently touching one another at the ends of the tracks. It is concluded that particles are shot out of the radioactive atom at high speed and that when moving fast they are able to activate only a few silver grains, but that, as they are progressively slowed down, more and more silver grains are activated. In consequence, the density of the tracks when developed increases towards their ends, until the particles are finally stopped and have no further energy available for the activation of silver. This observation is in accordance with the suggestion that tracks of this kind are produced by particles moving through the emulsion.

It may be argued that these experiments with radioactive substances provide the most direct evidence there is for the discontinuity of matter and, when they are taken in conjunction with demonstrations of the Brownian movement and of the behaviour of oil drops in Millikan's apparatus, it becomes increasingly evident that a theory of discontinuity is alone acceptable, as far as these phenomena are concerned. Further inductions will be required to extend the theory to other phenomena for which the evidence is less convincing.

# CHAPTER IX

# X-RAYS

TOWARDS the close of the nineteenth century much interest was taken in the fluorescence excited by cathode rays upon the walls of a glass tube which was exhausted to a pressure of about 0·01 mm. of mercury. In 1895 Röntgen, professor of physics at the University of Wurtzburg, covered a pear-shaped discharge tube with black paper and found that fluorescence was excited on a screen of barium platinocyanide which was placed some distance from the tube. He deduced correctly that invisible rays were passing from the tube to the screen. No sooner had he published his discovery than his work was repeated in many other physical laboratories and it was at once confirmed that these X-rays not only cause fluorescence in certain materials and penetrate solid matter, albeit with a diminution in intensity, but they also ionize gases through which they pass and readily affect a photographic plate.

For some years the nature of X-rays was uncertain. They could be scattered by matter on which they fell, seeming to indicate that they should be regarded as a radiation, something like light. On the other hand, the property of ionizing gases through which they passed seemed to indicate that they consisted of streams of corpuscles. Attempts to diffract them with a fine slit failed, showing that if they had the nature of waves their wavelength must be exceedingly small, perhaps of the order of one A.U.

In 1912 the wave nature of X-rays was established by the crucial experiment of M. von Laue of Munich. He was aware that the distances between atoms in a crystal are about one or two A.U. and that the atoms must be arranged in rows. The crystal might therefore act as a sort of diffraction grating which would give some kind of interference effect if the X-rays incident upon it had a wave nature, but could hardly do so if they were streams of particles. The experiment was tried at von Laue's suggestion by Friedrich and Knipping, two research students, and ultimately succeeded. A fine pencil of X-rays passing normally through a thin crystal plate was found to give a diffraction pattern of spots upon a photographic plate. This fundamental experiment has proved to be of immense importance for two reasons. It finally settled the question of the nature of X-rays and gave a means of measuring their wavelength : it also led to the foundation of the great branch of physics known as X-ray crystallography.

Sir Lawrence Bragg, writing in *Nature* (January 7th, 1950, Vol. 165), said : " I feel that of all living scientists I owe most to Professor Laue for making this discovery. I was just starting my career when it was announced : it decided the subject of my first researches and it has formed the basis of my scientific work ever since. The discovery opened up new vistas, a new science has been born as the result of it. . . ." The fundamental experiment can be performed in the school laboratory and, if a little trouble is taken, it may be done with apparatus that is largely home made.

### (1) OPTICAL MODEL EXPERIMENT

It may be of value in opening the subject with students who have not hitherto worked with X-rays to consider an optical analogy which is more nearly within the range of their experience. The diffraction grating is a well known piece of apparatus and inspection of an optical grating with a microscope at a magnification of × 500 or so gives ocular proof of the discontinuity of its structure. The lines can be clearly seen and the evidence for their existence, quite apart from any knowledge of the ruling engine by means of which they were produced, is as good as any other evidence given by optical images. If a narrow beam of light is allowed to fall perpendicularly on an optical grating of sufficient fineness, say, one having more than about 10,000 lines to the inch, spectra are produced on either side of the central spot. If monochromatic light is used and the beam is narrow, each spectrum appears as a coloured spot. If three or four gratings are superposed, being crossed in different directions so that in no case are their rulings parallel to one another, a pattern of spots is produced which in some ways resembles a Laue figure (see Plate III, C). An adjustable apparatus for carrying out this model experiment can easily be made with four coaxial brass tubes chosen to fit one within the other. Small replica gratings on celluloid can be purchased for a few shillings and are suitable for mounting in the four tubes. The arrangement is illustrated in Fig. 47.

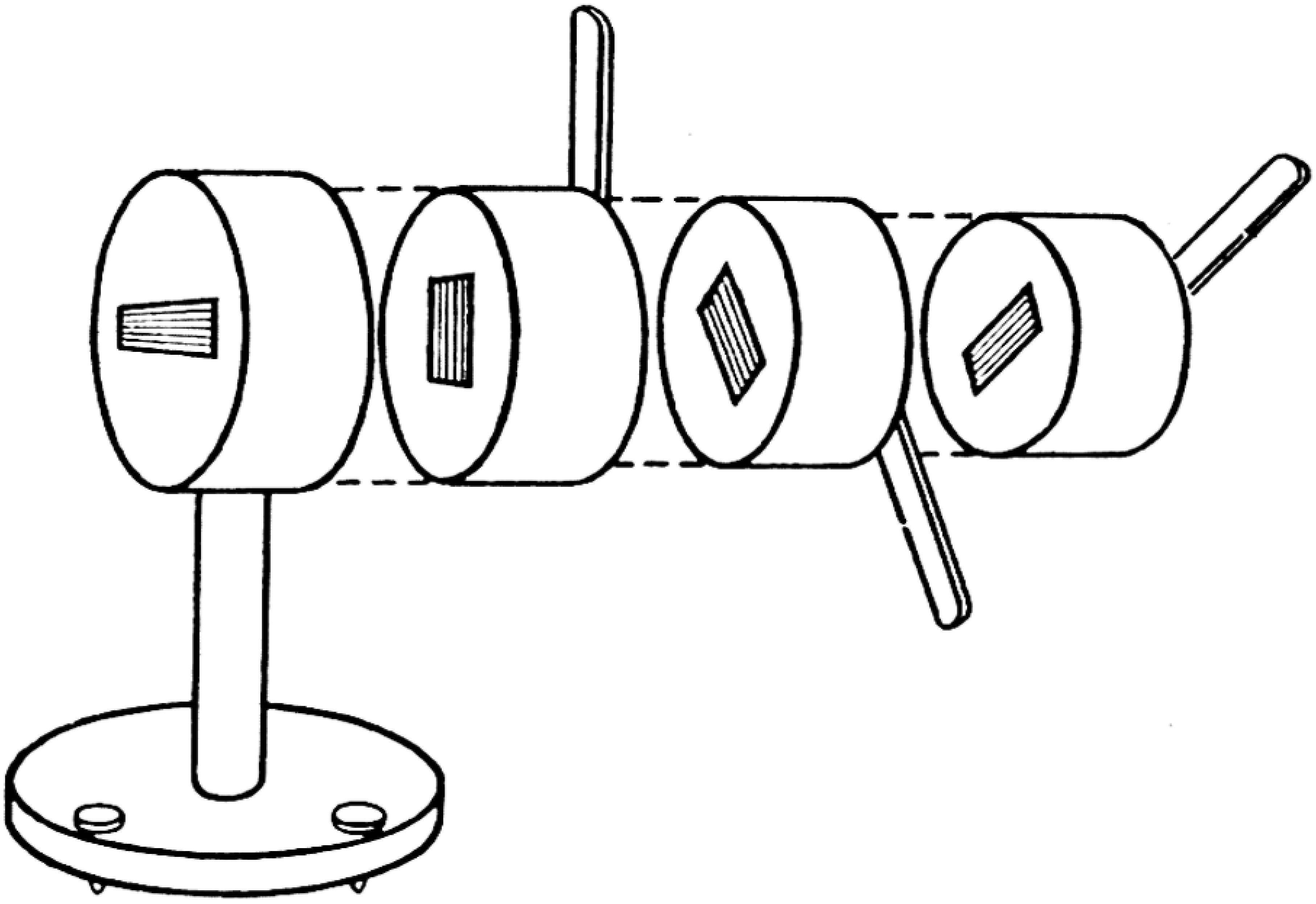
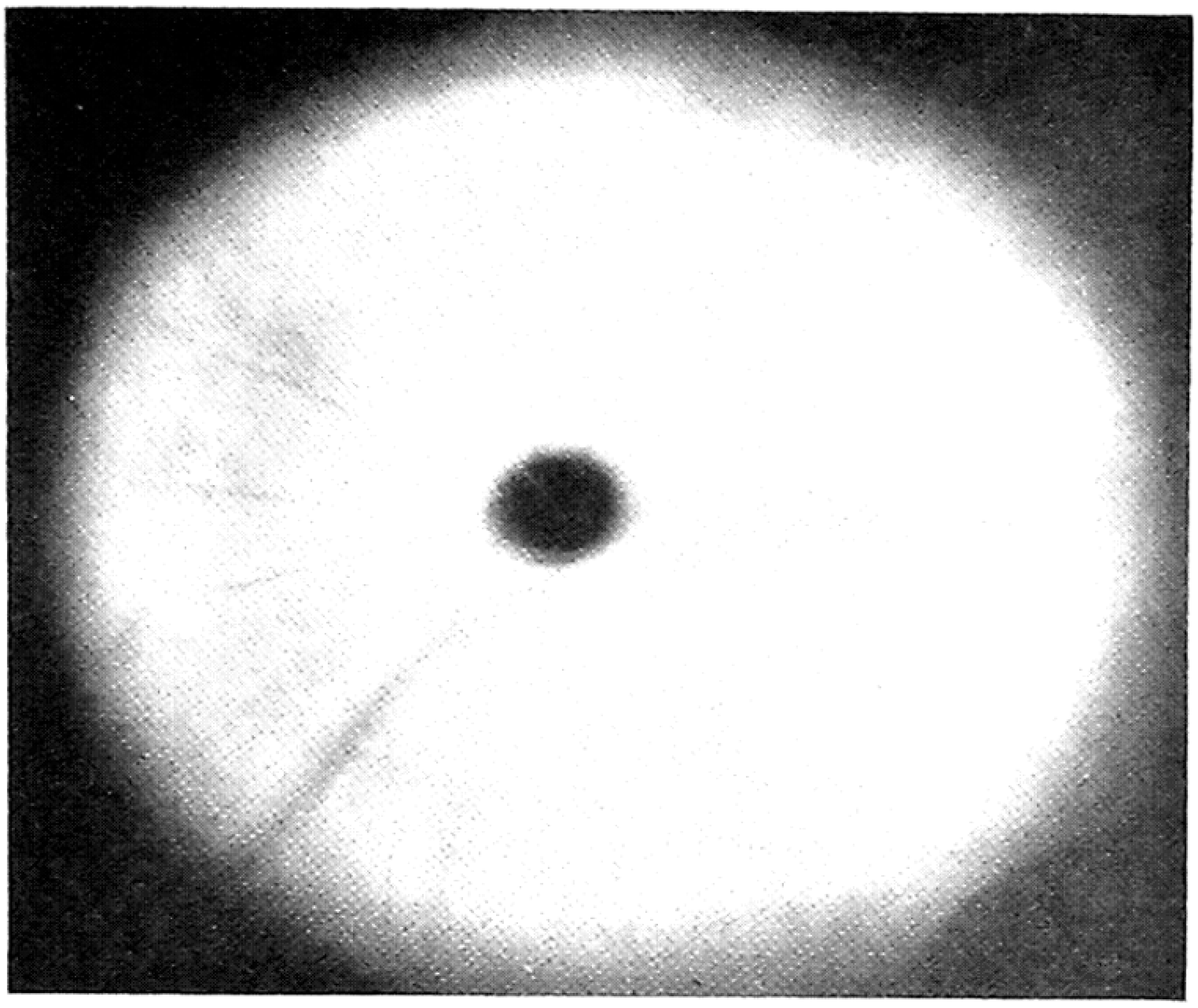


FIG. 47. Four concentric tubes each carry a replica diffraction grating, the angles between whose lines can be varied at will.

A narrow beam of nearly parallel light is formed by placing a metal screen with a small circular hole, say 1 mm. in diameter, between the condenser and the projection lens of a lantern which is illuminated with an arc or a pointolite lamp. Those positions of the metal screen and the projection lens are found for which the smallest possible image of the circular hole is

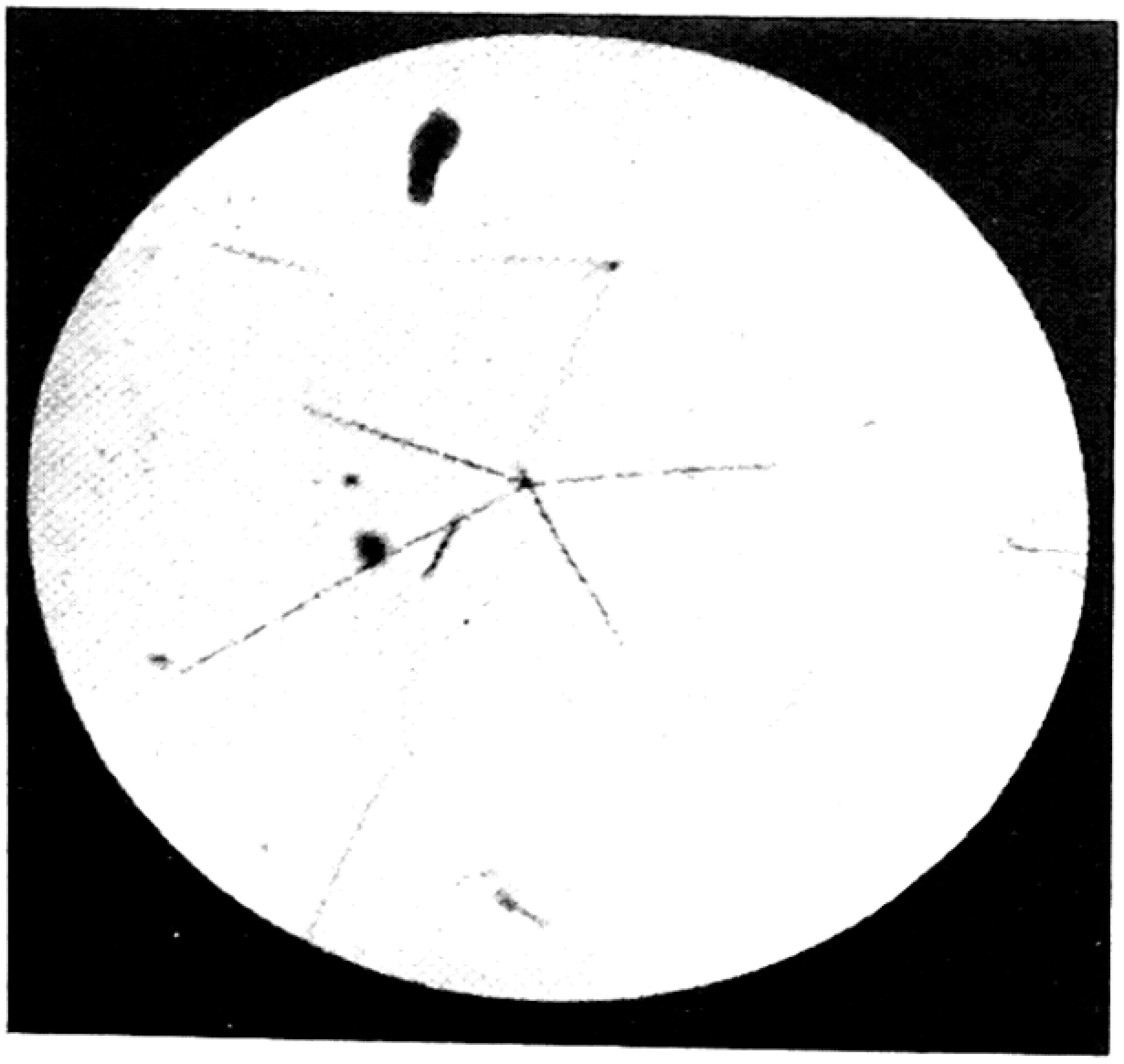
# PLATE III



A.

CLOUD CHAMBER TRACKS FROM RADIUM.

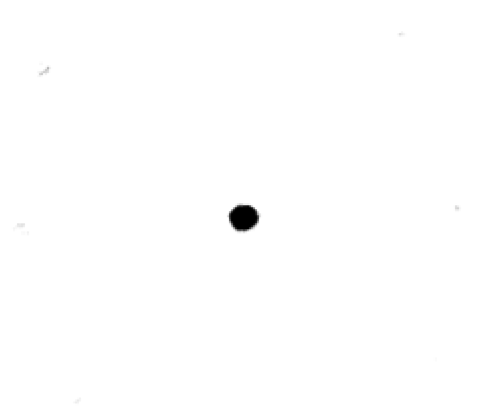
*Photograph by J. H. Locket.*



B.

A THORIUM STAR.

*Photograph by the Author.*

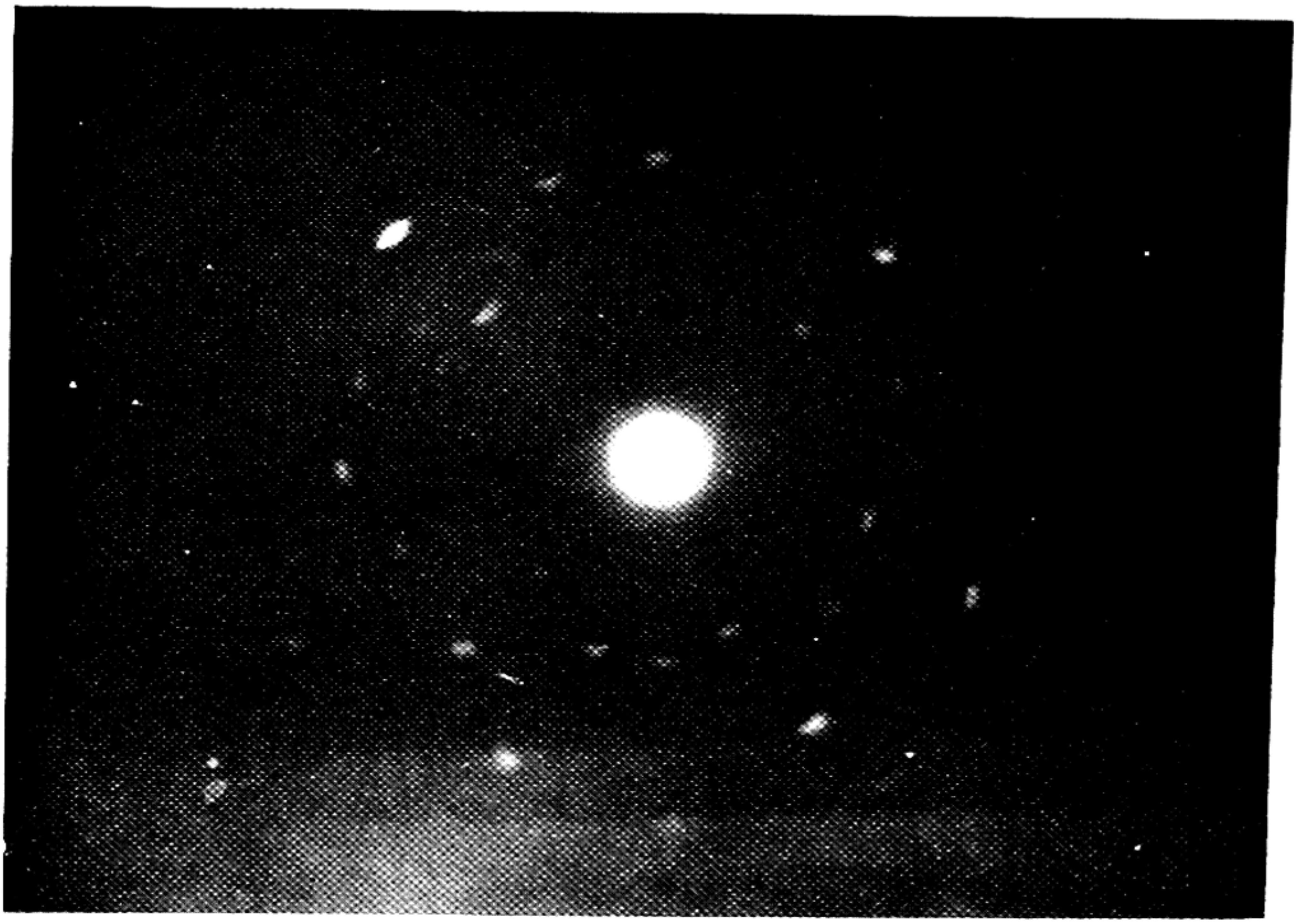


C.

OPTICAL PATTERN PRODUCED WITH FOUR CROSSED GRATINGS.

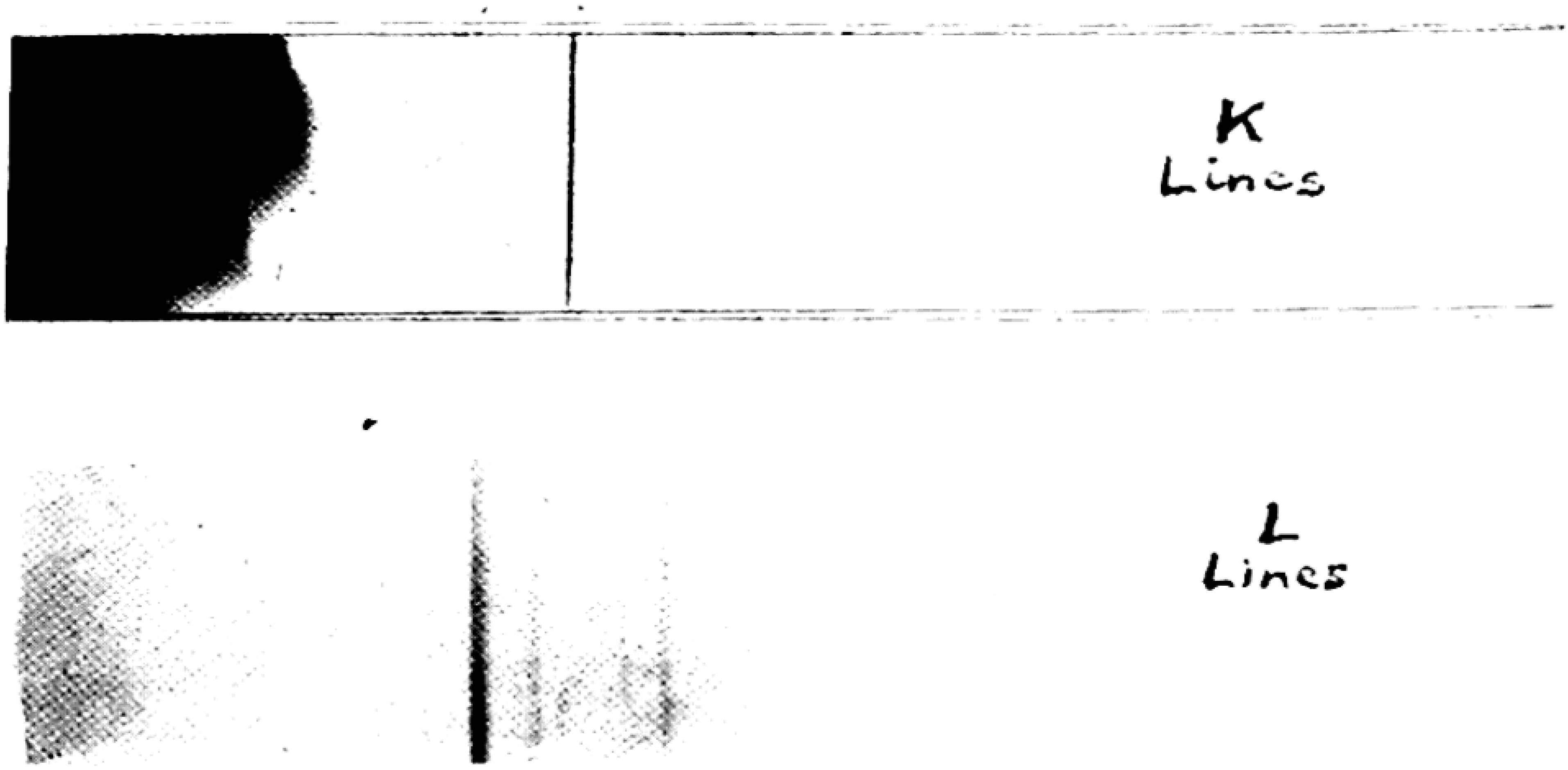
*Photograph by the Author.*

# PLATE IV



*Photograph by the Author.*

A. Laue Spots of Rock Salt Obtained by Means of the Demountable X-ray Tube Described in the Text.



*Photographs by the Author.*

B. X-ray Spectra of Molybdenum Obtained by the Bent Crystal Method of Mlle. Cauchois Using the Demountable X-ray Tube.

formed on a white screen. The three or four crossed gratings are then placed beyond but close to the projection lens and the diffraction pattern may be received upon a white screen or may be photographed. Plate III, C, shows the kind of pattern that may be formed. It was obtained by using four crossed gratings at 45° to one another together with a green filter. Velox paper, W.S.G. 2S, was used at a distance of 5 or 6 cm. from the gratings. The exposure time was 60 seconds. The spots on the photographs represent areas on the screen where rays diffracted by the different gratings reinforce one another sufficiently strongly to produce an image. The conclusion to be drawn from this optical experiment is that the pattern of spots is produced by the transmission of visible light through crossed gratings whose spacing is known or can be measured. Of course the wavelength of a particular monochromatic ray can be calculated from a knowledge of its angular displacement when diffracted and of the distance between adjacent lines on the grating.

The analogy here proposed is that since crossed gratings of known spacing can be made to give a pattern of spots by the transmission of light, it is at least possible that a crystal plate which gives a somewhat similar pattern by the transmission of X-rays may possess structural regularities. If rows of particles exist in crystals so as to give an arrangement something like the criss-cross produced by the lines of the crossed gratings, it would perhaps serve to explain the formation of Laue spots with X-rays. This suggestion is of course in accordance with the views that have been held by crystallographers since the time of the Abbé Häuy. The phenomena of cleavage and the existence of glide planes require that the structure of crystals should be of this kind. In short, a consideration of the Laue spots leads to the inferred conclusion that matter in the crystalline state possesses a discontinuous nature. The analogy is not put forward as a proof of anything. It is an aid to understanding ; a teaching device.

## (2) LAUE SPOTS

It is not sufficient to inspect photographs of Laue spots taken perhaps in some University laboratory with the expensive specialized equipment proper to such institutions. It is desirable that fundamental phenomena should be shown to boys at school as soon as discussion of them arises. Laue spots can be produced with a home-made X-ray tube, provided an induction coil which will give a spark of 6 or more inches is available. The photograph reproduced here was obtained with a coil which is capable of giving a 10-inch spark. The method employed is described below.

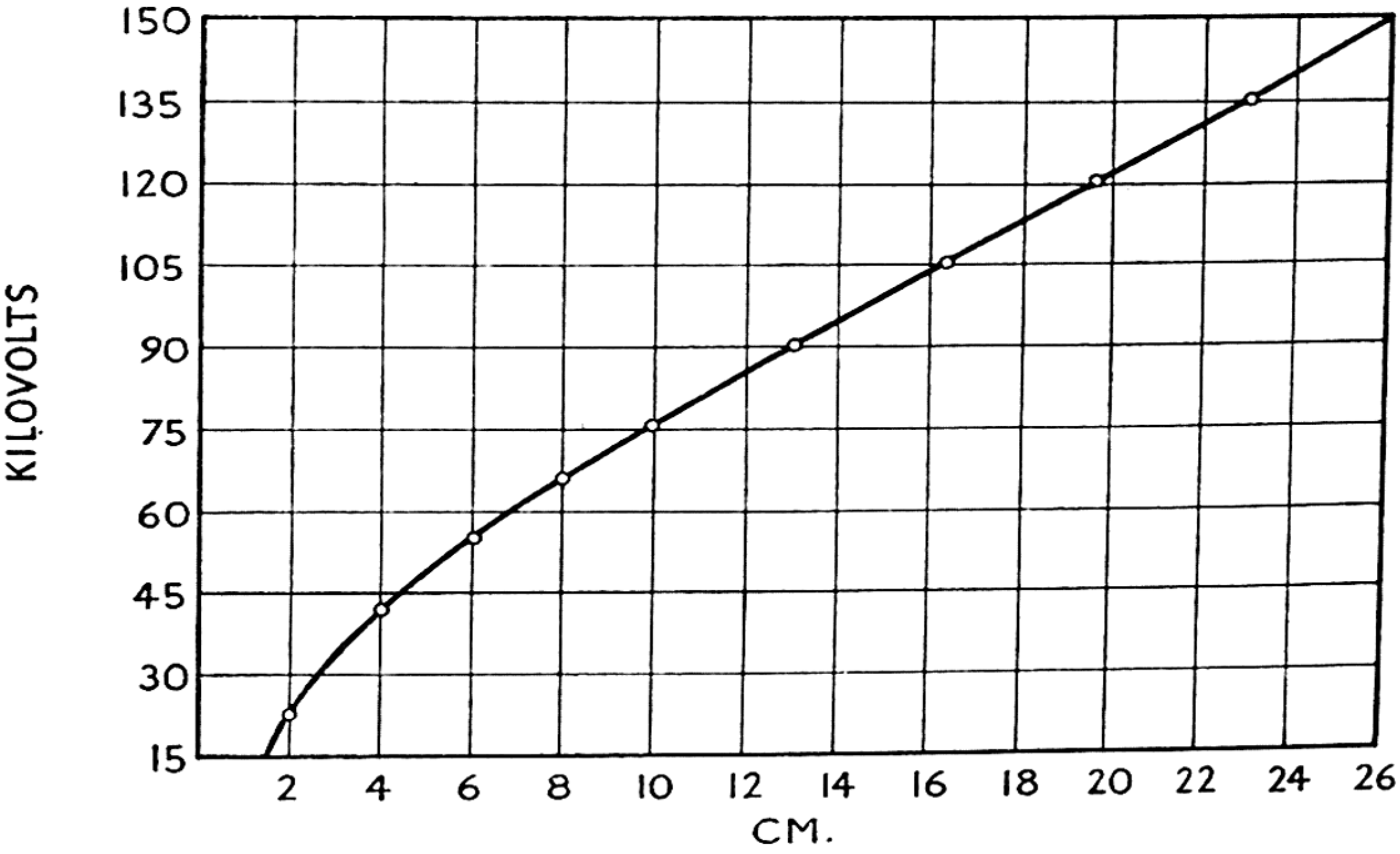


FIG. 48. Curve showing voltage required to give sparks, between points in air, of the lengths indicated.

First, it is useful to have some knowledge of the relation between the kilovoltage of the secondary of an induction coil and the length of spark between points in air. The tables given by authors differ among themselves and sometimes fail to indicate the conditions of sparking. The potentials should be given clearly in terms of peak volts. The graph given here is drawn from the data supplied on p. 113 of Kaye and Laby's *Tables of Physical and Chemical Constants* (tenth edition). The lengths of spark are for peak voltages and for gaps between the points of No. 00 new sewing needles. The curve is apparently reliable up to 75 Kv., but seems to be continued beyond that value by extrapolation.

If it is wished to measure the secondary voltage of an induction coil a xylene potentiometer may be employed. The secondary terminals of the coil are connected to two wires sealed 60 cm. apart through the walls of a glass tube which is closed at both ends, a side tube being attached for filling with xylene. A third wire is sealed between the other two, at a distance of 2 cm. from one of them. These two adjacent wires are connected to an electrostatic voltmeter reading to 3,000 volts and the voltage given by the coil can be rapidly, if only approximately deduced from the indications it gives.

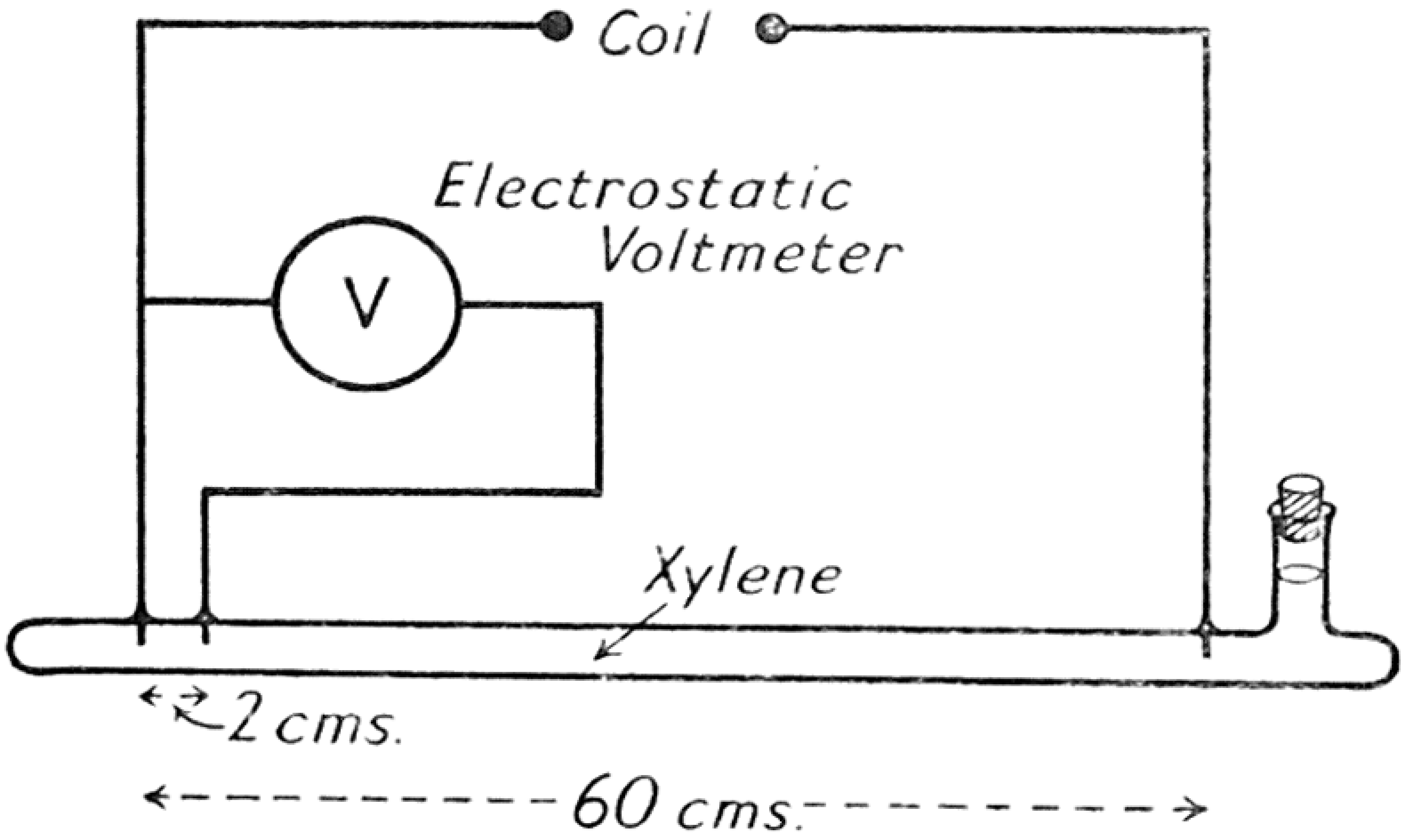


FIG. 49. Xylene potentiometer for measuring the P.D. given by an induction coil.

If a powerful modern X-ray set is available it is possible to produce Laue spots with an exposure of five minutes or less. Another five minutes will serve to develop and fix the film, which may then be projected as an experimental demonstration in the course of a lecture. If the only X-ray tube to be had is the old type gas tube this will not be possible, as the exposure required may be hours rather than minutes, even supposing that wandering of the cathode spot or some other difficulty does not arise to give a poor result. The method recommended here presupposes some familiarity with vacuum technique and sufficient workshop skill for the manufacture of a hot filament tube. The necessary apparatus is shown in the diagram :

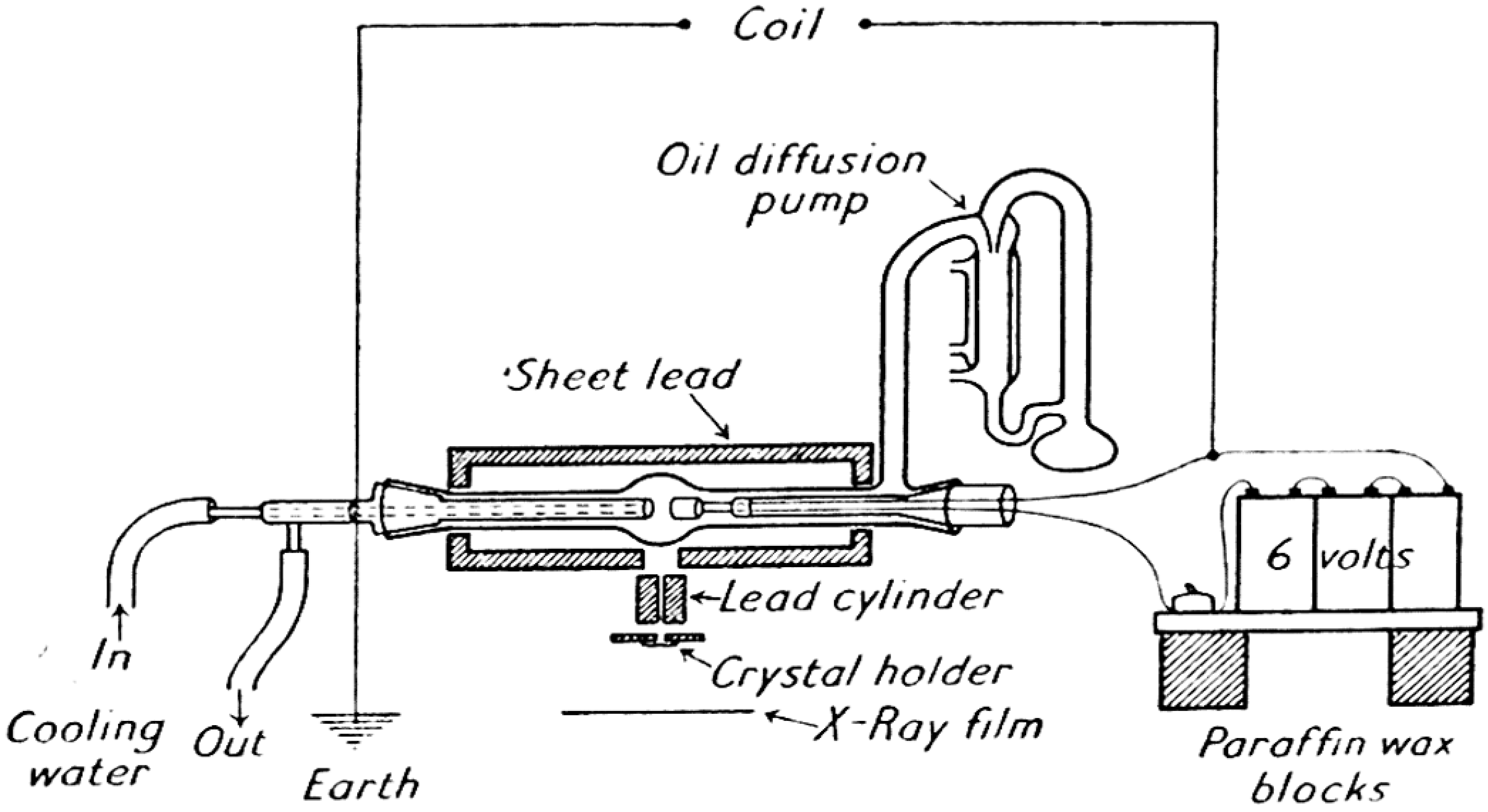


FIG. 50. Diagrammatic scheme for the production of Laue spots using a home-made X-ray tube.

In the absence of an H.T. transformer and rectifier circuit, use was made of a large induction coil which is capable of giving an 8–10-inch spark when supplied with current at 12 volts. This arrangement necessitates batteries to heat the filament. Together with their rheostat and ammeter they must be well insulated by means of a table supported at least 4 inches from the bench on legs made of paraffin wax or some other insulator. The anode of the X-ray tube must, of course, be connected to the positive terminal of the induction coil and should be efficiently earthed. It is not enough to rely on the cooling water. A copper wire should be taken to the nearest water pipe or other satisfactory earth connection.

If the X-ray intensity is to be that given by less than 1 m/a.

of tube current, the slit defining the beam of X-rays must be as close to the anode as possible and the old type of gas tube which employed an anode at the centre of a large glass bulb is at once seen to be unsuitable. A Coolidge type tube is easy to construct and need not be more than 4 cm. in diameter at the anode. As it will be of the demountable type it will have to be continuously pumped, but there will be no difficulty in replacing the filament when necessary. The tube described here can be made by hand without machine tools and, once the necessary materials for its manufacture have been collected, it requires the expenditure of little time and only moderate skill. The body of the tube is of Pyrex glass and may be 30 mm. in diameter and about 30 cm. long. The purpose of the bulb in this tube is to ensure that the glass is as thin as possible consistent with sufficient mechanical strength. The provision of an aluminium window introduces complications and may be dispensed with. The dimensions are shown in the figure.

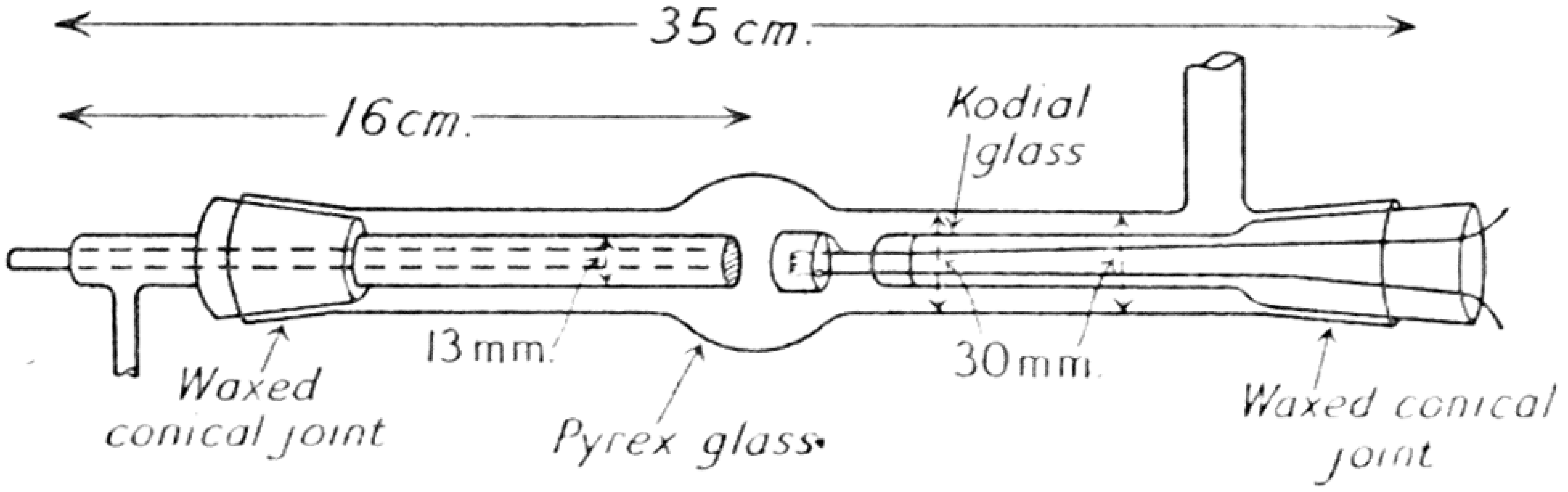


FIG. 51. Dimensioned diagram of a demountable hot cathode X-ray tube.

*Cathode Assembly.* The part of the X-ray tube that is likely to be the most difficult to make is the glass-metal seal for the hot cathode, but full instructions for making a seal of this kind have already been given in the section on thermionic emission (p. 33). If the instructions have been carried out successfully, all that is required is the addition of a Wehnelt cylinder, which serves to concentrate the thermionic electrons in a stream directed towards the anode surface. The cylinder is made of sheet nickel, a tang of which encircles one of the filament supports. The other filament support must be insulated from the base of the cylinder. This is done by means of a perforated disc of mica. The Wehnelt cylinder must be slipped over the filament supports before their ends are bent to receive the tungsten filament. When this has been firmly attached, the cylinder is positioned so that the filament is inside the cylinder and is a few mm. from its open end. The sheet nickel tang is then pressed firmly round the supporting wire to hold the cylinder in place. The construction may be seen in the diagram (Fig. 52).

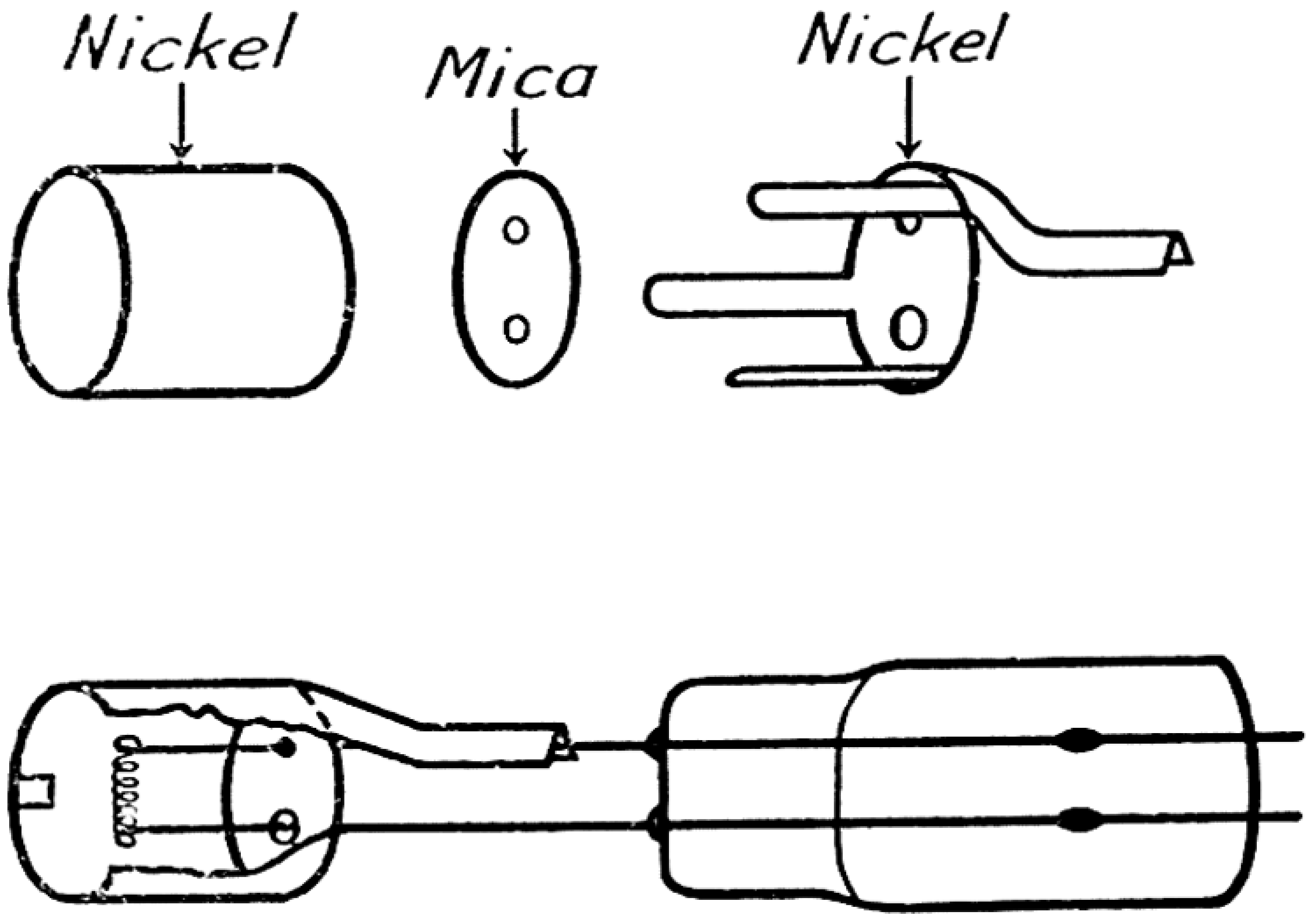


FIG. 52. Method of construction of the Wehnelt cylinder.

The anode can be made without the use of machine tools. Quite apart from the desirability of keeping the target cool for other reasons, it must be water-cooled in a demountable tube to ensure the efficiency of the waxed joint. The anode may be of copper, or may terminate in a plate of molybdenum, tungsten or platinum, according to the type of characteristic radiation required. If, as is intended here, the tube is to be used for the production of Laue spots, the so-called " white " radiation is required and any non-volatile metal may be used for the target. If much power is to be dissipated at the anode, the target metal should be in intimate thermal contact with the end of the anode tube. Silver soldering will serve in some cases, but it is better to avoid it, if possible. Modern targets are nearly perpendicular to the cathode stream of electrons, those X-rays being used which come off nearly at grazing incidence, usually 6°. The distance between cathode and anode is 1–2 cm., a short distance being preferred in order to reduce the chance of puncture of the tube when the H.T. is applied. A high vacuum of the order of $10^{-4}$ mm. of mercury, or better, must be maintained while the tube is being run. A satisfactory anode assembly is illustrated in Fig. 53.

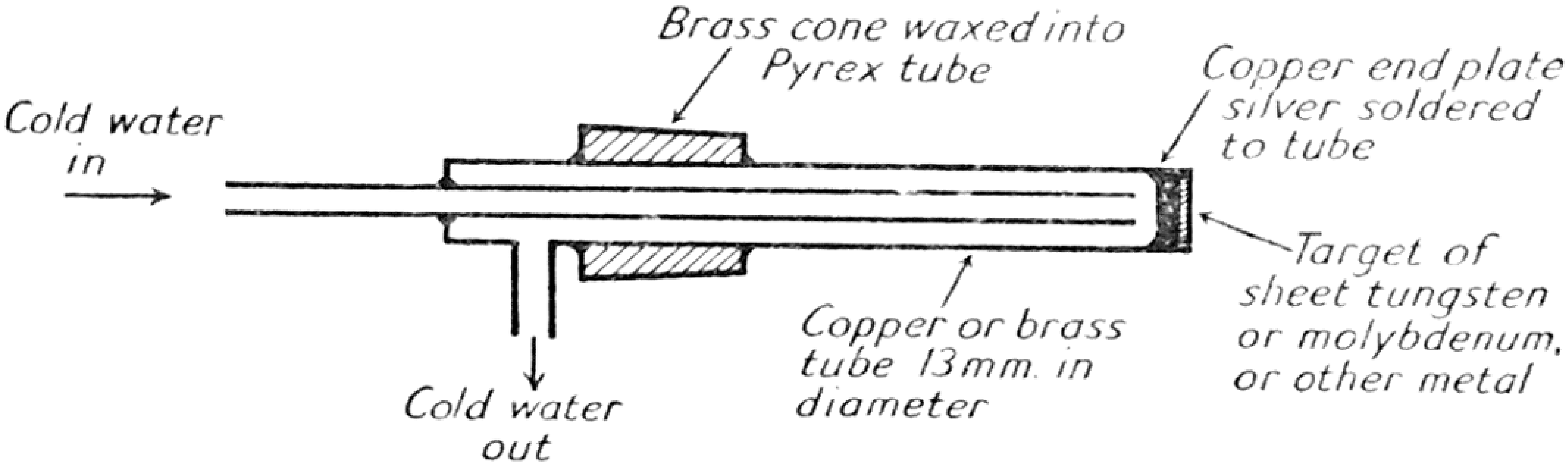

Brass cone waxed into Pyrex tube
Copper end plate silver soldered to tube
Cold water in
Target of sheet tungsten or molybdenum, or other metal
Copper or brass tube 13mm. in diameter
Cold water out

FIG. 53. Details of the anode assembly. It is all metal. The target slopes at about 6° to the plane perpendicular to the axis of the tube.

The anode tube may have a plain copper end silver soldered to the brass tube, or may have an insertion of some other metal. Platinum foil is to be found in most laboratories and is quite suitable. Molybdenum and tungsten sheet can now be purchased for a shilling or two per square inch and should be highly polished before use. Both these metals may be silver soldered to copper using borax as a flux, but if it is required to change the target metal, say for experiments on characteristic radiation, it may be convenient to construct the copper tip of the anode tube with a slot into which rectangular plates of the metals can be inserted, or alternatively, discs of tungsten or molybdenum can be forced into a circular depression.

The brass anode tube and the cathode tube are waxed in position by means of conical joints with Edwards' W.E. wax or some other suitable composition of low vapour pressure. A side tube of large diameter, that is, 20–25 mm., is fused direct to an oil diffusion pump, thus obviating the use of a liquid air trap. There should be a reservoir on the high pressure side of the pump containing phosphorus pentoxide. The silicone oil DC 702, which has recently been produced in the U.S.A. by the Dow Corning Corporation and is obtainable in England, is perhaps the best liquid to use in the pump. It may be electrically heated by an immersed helix of nichrome wire, if such a pump is available or can be made. Otherwise, external heating by electricity or by a gas flame will do, but better control of temperature is obtained with internal heating. A fore-pump giving a vacuum of better than 0·1 mm. of mercury is required with an oil pump. Any of the scraping-vane types of rotary mechanical pump will serve.

The reader may care to be reminded of the details for exhausting a piece of apparatus with this equipment. First, turn on the water supply to the diffusion pump. When it is certain that all waxed joints are cold, evacuate with the fore-pump. The degree of vacuum obtained can be judged with a small induction coil applied to the metal electrodes of the X-ray tube, or a high frequency tester may be used. The heater of the diffusion pump may then be turned on and the vacuum of the X-ray tube should be tested until no discharge will pass from cathode to anode. The filament current may then be turned on. It must now be established that the cooling water is flowing through the anode tube. Of course, the same stream of water may be used for the diffusion pump and the anode cooling circuit. As the anode is earthed there will be no inconvenient electric fields established. The H.T. may now be applied to the X-ray tube, care being taken that the lead shielding is in place and that the polarity of the applied potential is correct. *Particular care must be taken to turn off the H.T. supply before attempting to alter the filament current, as the filament circuit apparatus, standing on its insulated table, is at the full potential of the induction coil.* A fluorescent screen is used to judge whether X-rays of sufficient intensity are emerging from the window in the lead shield which surrounds the X-ray tube. The room should be darkened for this inspection.

When it is certain that X-rays can be produced at will, the induction coil is disconnected for safety, and the crystal holder with slit and photographic film are put in place. The slit may consist of a lead cylinder, 1 cm. in diameter and 3 cm. long, with an axial hole not larger than 1 mm. in diameter. The slit is attached firmly to the lead shielding of the X-ray tube and is placed as close as possible to the surface of the X-ray tube, so that a beam of X-rays passes through it. This adjustment is carried out with the aid of the fluorescent screen and must be done with great care. It is useless to proceed unless the alignment of the slit is satisfactory. The crystal holder is a brass plate having a conical hole 1 mm. in diameter at its smaller end, which is turned away from the slit, at a distance of about 5 mm. from it. A thin plate of the crystal to be investigated is then cemented over the hole in the crystal holder. Rock salt or zinc blende can readily be cleaved to give a crystal plate from 0·5 to 1·0 mm. in thickness. The alignment of the slit and crystal holder should again be checked with the fluorescent screen before an attempt is made to take a photograph. The film may be Kodak Industrex D with emulsion on both sides, of quarter-plate size. It is placed about 4 cm. from the crystal and an exposure of at least one hour is required. The current through the X-ray tube, which may be measured by putting a well insulated milliammeter in the circuit, is less than 1 milliampere. If it is found that the X-ray tube ceases to give X-rays after working for a few minutes, owing to the development of space charge or for some other reason, it should be allowed to cool for a few minutes with the filament current and the H.T. turned off. The photograph reproduced here was taken by giving the film a total of sixty-four minutes' exposure, the X-ray tube being run for four minutes and then being allowed to cool for four minutes, alternately. The filament current was 3·3 amperes. A larger current caused a diminution in X-ray intensity, as judged with the fluorescent screen, probably owing to a space charge effect. The disposition of the apparatus is shown in the diagram (Fig. 54).

The film is developed in the ordinary way with metol and sodium carbonate. As it has emulsion on both sides it should be supported in the developing dish on a T of glass rod and the dish should be rocked throughout development, which is complete in three minutes. The film is then washed rapidly in running water and fixed See Plate IV, A, facing p. 105.

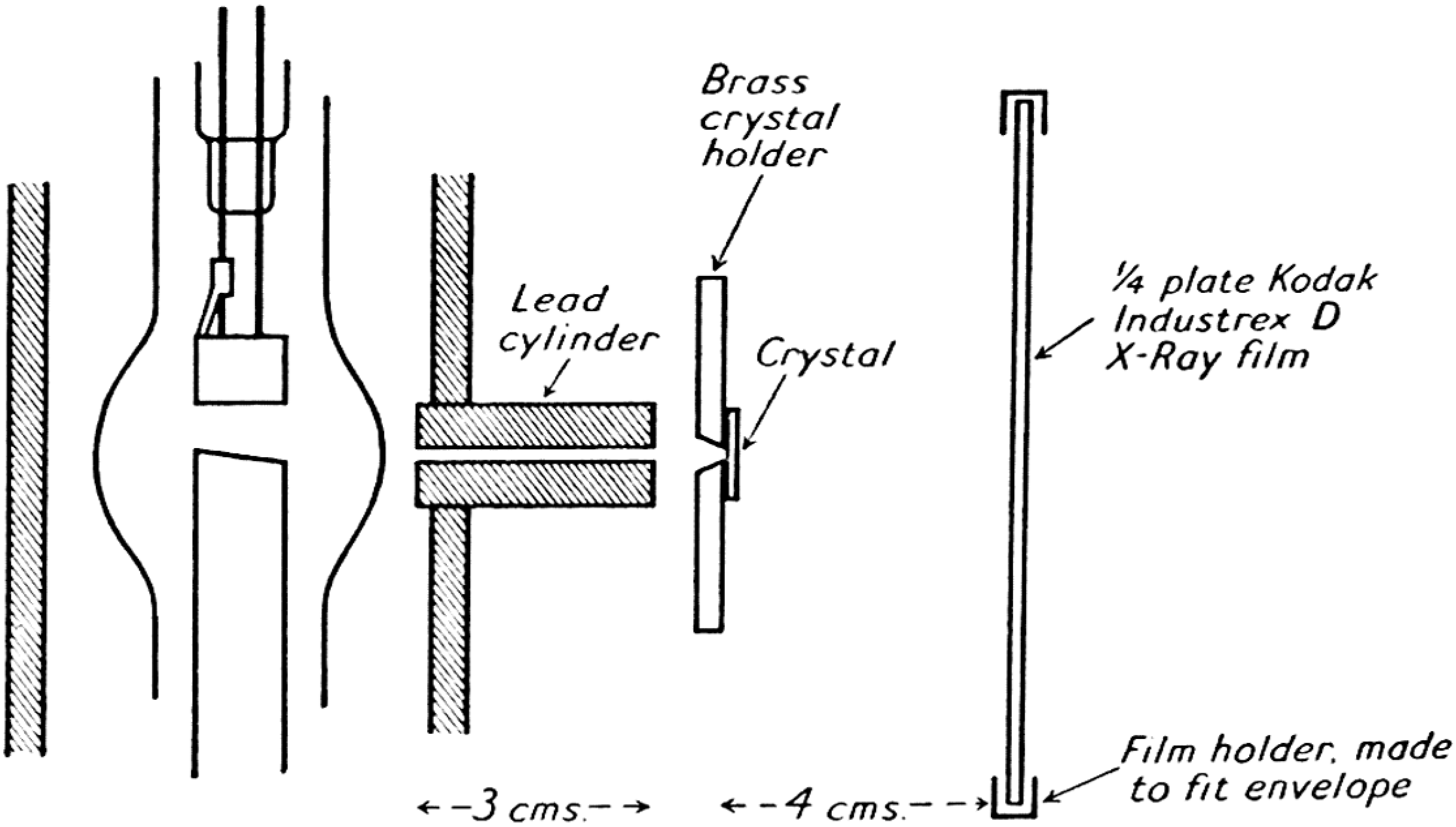

Brass crystal holder
Lead cylinder
Crystal
¼ plate Kodak Industrex D X-Ray film
Film holder, made to fit envelope
←–3 cms.–→
←–4 cms.––→

FIG. 54. Arrangement of X-ray tube, slit, crystal carrier and X-ray film for the photography of Laue spots. The dimensions given are of importance.

It is well worth while to take the trouble to get a Laue photograph, as the experiment provides a convincing argument for the discontinuous nature of crystalline matter on the smallest scale, thus reinforcing arguments from crystalline form, cleavage and glide. The discontinuity of the surface of a diffraction grating can be seen in the microscope and the similarity of the effect produced with X-rays on their passing through a crystal plate leads to a strengthening of the probability of a regular arrangement of particles of atomic dimensions in crystalline matter.

# CHAPTER X

# SPECTRA

In his investigations of the composition of sunlight Newton had used a round hole in a shutter as his source and does not seem to have realized the advantages that would have followed had he used a narrow slit. In 1802 Wollaston observed black lines crossing the spectrum of the sun when such a slit was used, but he did not pursue the subject. It was Fraunhofer of Munich who made the greatest advances in the design of spectroscopes. By the use of a narrow slit, a lens to render the incident light parallel, a prism made of his own good quality optical glass and a telescope to bring rays of the same colour to a focus, he introduced most of the features of the modern spectroscope. In 1814, with his arrangement of optical parts, he rediscovered the dark lines which cross the spectrum of the sun and mapped many of them with great precision. The explanation of their presence as absorption lines was due to Stokes in 1850.

A second contribution made by Fraunhofer to spectroscopy, and indeed to physics as a whole, was his discovery of a way of measuring the wavelength of light, a method which is still in use to-day. Parallel light from a slit was allowed to fall normally on a large number of equidistant parallel slits, which constitute a grating. Part of the incident light goes straight on and is focussed by a lens, giving an undeflected image of the source. But on either side of the central image, rays from any two adjacent slits will have traversed different lengths of path and if this difference happens to be a whole wavelength of a particular colour of light, or an integral multiple of a whole wavelength, the two rays will reinforce one another and a bright image of the slit is formed. As there is a simple geometrical relationship between the grating spacing, the wavelength of the light and the angle at which reinforcement takes place, the wavelength can be measured.

Fraunhofer first used a grating made by winding fine silver wires on a brass frame and measured the wavelengths corresponding to some of the principal dark lines, or Fraunhofer lines, of the solar spectrum with surprising accuracy. This work was published in 1821. Later he ruled parallel lines on flat glass plates. One of these had about 7,000 lines to the inch and with it he measured the wavelength of the D line of sodium with an accuracy of 1 part in 2,000.

Some of the finest gratings have been made by Rowland of Johns Hopkins University, U.S.A. He developed a method of making a screw of extremely accurate pitch, upon which a ruling machine must depend. A grating for ordinary use may have about 15,000 lines to the inch but Rowland has made gratings with 100,000. In 1881 he conceived the idea of ruling gratings on the reflecting surface of a concave mirror, thus producing another advance in spectroscopy.

It was recognized in 1859 by Bunsen and Kirchhoff that under given conditions each of the chemical elements emits a definite spectrum which is characteristic of it and that spectra can therefore be used to identify the elements, even when they are present in a mixture in very small proportions. Although it was realized that line spectra were characteristic of atoms, it was not until 1885 that any mathematical relationship was discovered between the wavelengths of the different lines of any one element. In that year Balmer discovered such a relationship in the visible hydrogen spectrum and thereafter the spectra of many of the elements were found to be built upon a similar plan. In the hands of later physicists, who had the advantage of more refined apparatus as well as the accumulated experience of their predecessors, the structure of the outer parts of the atom became revealed. Enormous advances have been made in the last few decades and the spectroscope is regarded as one of the most important instruments we possess.

### (1) THE GRATING SPECTROMETER

It is surprisingly easy to construct a spectroscope which will disperse the visible lines over a scale a foot or so in length.

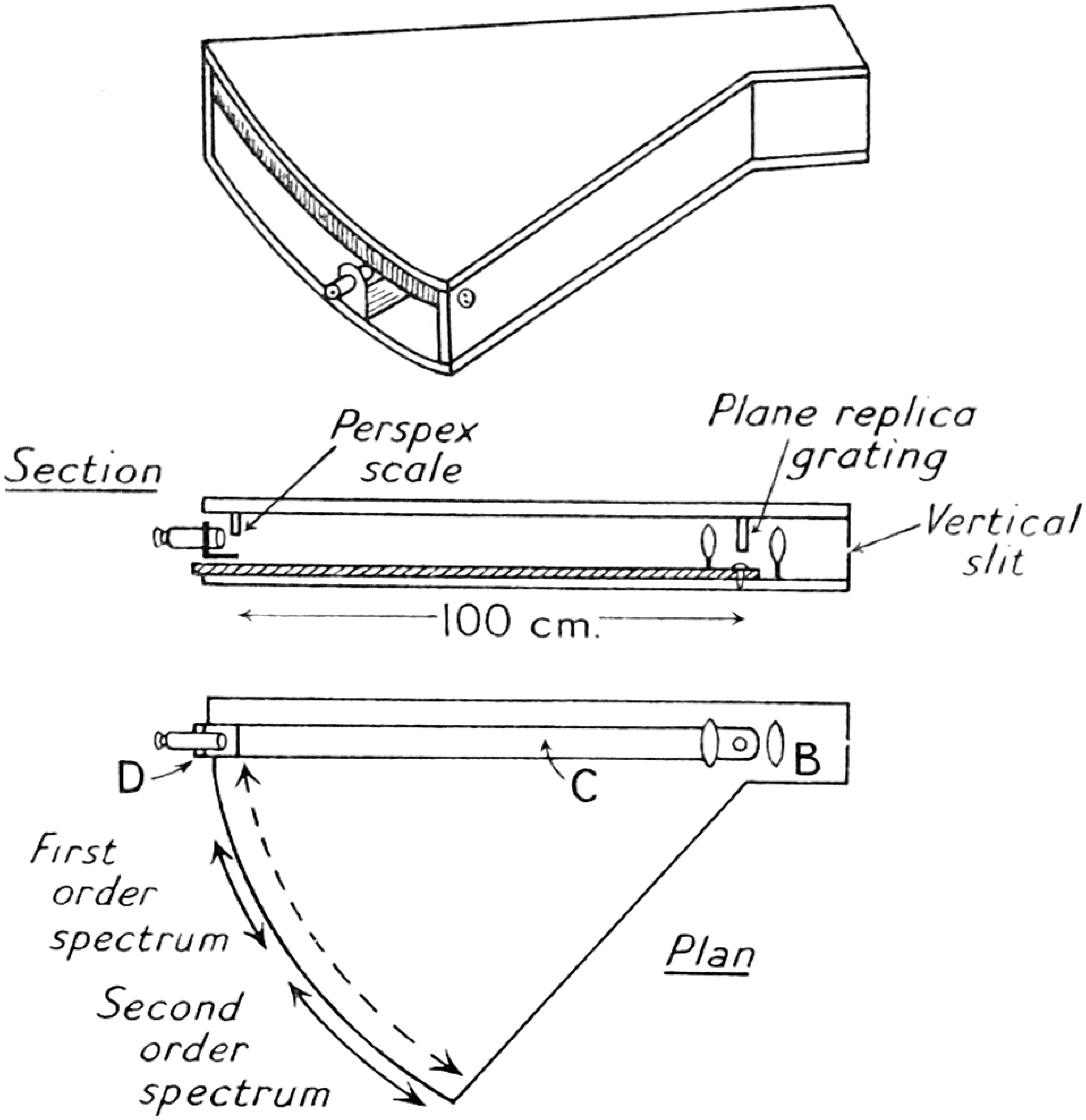


FIG. 55. Construction of a simple grating spectrometer. If the grating has 14,400 lines per inch and the telescope objective has a focal length of 100 cm., the visible first order spectrum will be about 8 inches long.

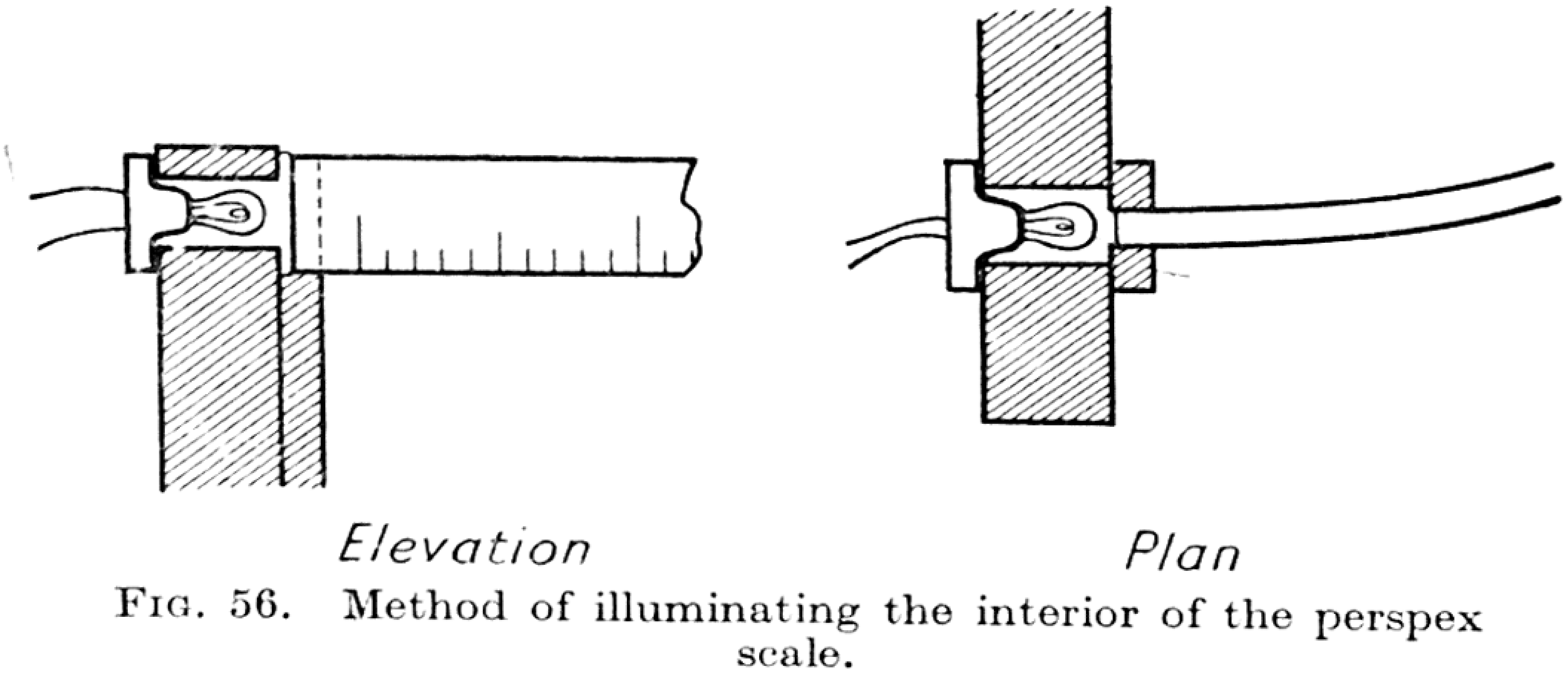
With eyepiece magnification and a sufficiently bright source of light thousands of lines can easily be seen and mapped. The essential parts of the instrument are a good replica diffraction grating of about 15,000 lines to the inch and a lens which need not be achromatic, of focal length about 100 cm.

Most schools possess such a grating, but if none is available, a replica plane transmission grating of good quality can be purchased for about £2 *5s.* The lens, of focal length 100 cm. and 5 or 6 cm. diameter, will only cost a few shillings. Other essential equipment is a carbon arc, a slit of good quality, which can be made in the laboratory workshop without much difficulty, a collimating lens of 15–20 cm. focal length and a short focus lens as an eyepiece. If an achromatized Ramsden eyepiece is available it will do very well. It is important that the image should not be formed between the lenses of a compound eyepiece, as in the Huygens type, because it is proposed to form the image of the spectrum on a cylindrical surface which coincides with a transparent scale.

The spectroscope may be made largely of plywood. Two pieces of 5-ply or 7-ply are cut to the dimensions indicated. These two boards are held 7 or 8 cm. apart by stiff battens about 2 cm. in thickness. The end B is arranged to accommodate a vertical slit which should be adjustable and of the best quality. If the edges of the jaws of the slit are bevelled, the bevel should be turned towards the grating. A collimating lens is placed at B, its exact position being found by trial. It may be of 15 or 20 cm. focal length and, if circumstances permit, may be made adjustable for position by an externally controllable rack and pinion. This arrangement is useful for focussing the lines on the scale. The arm C is pivoted as shown and carries the objective lens of focal length 100 cm. It also carries the eyepiece D, which may be a single lens or, better, an achromatized Ramsden eyepiece. The focal length of the eyepiece should be about 2·5 cm. Above the pivot of the arm C the grating is fixed to the walls of the instrument. A black cardboard mask is provided so that only the ruled square of the grating is illuminated by the incident beam. The whole of the interior of the instrument is blackened with a dull black paint to avoid reflections.

If the instrument is to be used for the observation of first order spectra only the angle through which the arm can turn need not be more than about 30°, but if the second order is to be observed the angle should be 60°. It will be found that the extreme red of the second order overlaps the third order violet, but the separations of the lines are so large in the second order that its use is recommended if the grating and the lenses employed are good enough to give sharp images.

The scale is engraved upon a strip of perspex, 3 cm. broad, which is bent into the arc of a circle and is placed so that its lower edge, which should be polished, bisects the field of view in the eyepiece horizontally. The exact position for the scale must be found so that the image of the spectrum is formed upon it and can therefore be focussed together with the engraved marks upon the perspex. The scale may be illuminated by internally reflected light. A flash-lamp bulb, connected to a single accumulator, is buried in the wall of the instrument in such a way as to illuminate only the interior of the perspex. It is found that sufficient light is scattered at the furrows made in engraving the scale to allow the markings to be seen, but that this small amount of light in no way interferes with the observation of the spectral lines. Care should be taken to protect the surface of the perspex scale at all times during handling, as scratches inadvertently made upon it cannot easily be removed. The arrangement is illustrated below (Fig. 56):



*Elevation* *Plan*

FIG. 56. Method of illuminating the interior of the perspex scale.

The instrument may be used in daylight.

*Source of Light.* An electric arc is used as a source of heat, the temperature being high enough to volatilize all known substances. The instrument described here is for the purpose of identifying the chemical elements and for estimating approximately the proportions in which they are present in a mixture or a mineral. Thus rocks of all kinds may be introduced into the arc, as well as the simple compounds such as are kept in laboratories. The arc may be struck between carbon rods and made to play upon the substance to be investigated, or one pole of the arc may be of metal, if it is of sufficiently high melting point, or both poles may be of metal. The iron arc, which gives over 2,000 lines, many of them very strong, is used as a standard of comparison. The arc may be D.C., in which case a controlling resistance must be placed in the circuit to limit the current, or A.C., when an inductance is used for the same purpose. The best arrangement is to have the poles of the arc horizontal, so that the substances to

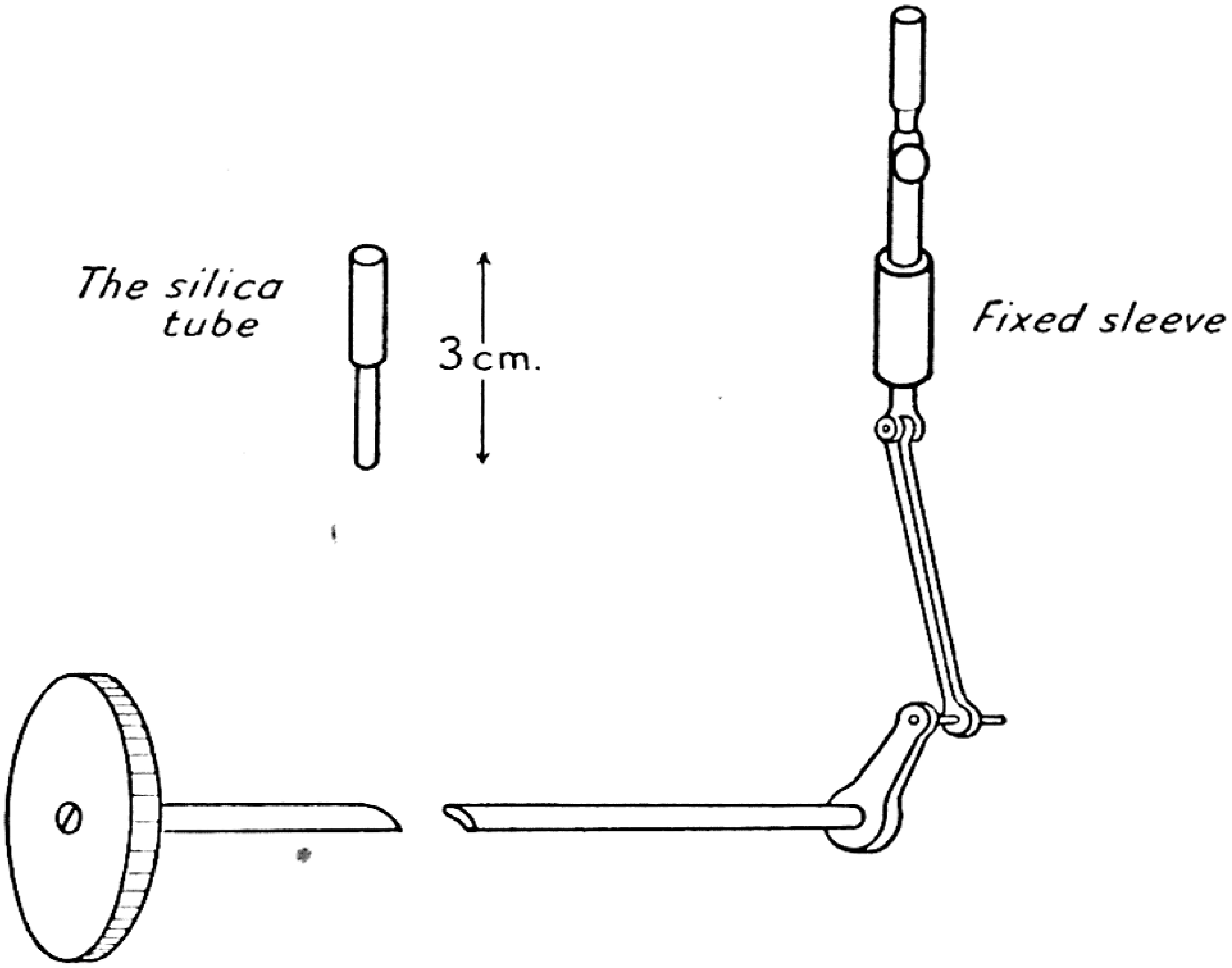


FIG. 57.

be introduced into the arc can be pushed up from below by raising a small platform of silica upon which a small heap of the powdered substance has been placed. The silica platform can be exchanged for some simple metal holder if a piece of rock is under investigation.

A very convenient arrangement for introducing powdered substances into the arc is shown in Fig. 57. The powder is placed in a small piece of silica tubing of about 3 mm. diameter which is closed at one end by a short length of silica rod. The tube and rod may be purchased from the Thermal Syndicate Ltd. for about 1*s*. 6*d*. per foot. The silica gives only one weak line in the visible spectrum. It is of wavelength 5948 A.U. in the orange and is soon recognized. The silica rod is held by a set-screw in a vertical brass tube which can be raised or lowered by remote control from the observer's seat. Some device should be included for moving the holder clear of the arc when it is required to change the silica tube. In this way the visible spectra of most of the elements can be produced and many of the constituents of a mineral can be recognized in as many seconds, once the characteristic groups or lines of the elements have been learned. The rate at which different substances are vaporized can also be controlled by the observer, as he has control of the distance of the silica tube from the flame of the arc. Further information on modern methods of spectroscopic chemical analysis, from the point of view of the teacher of chemistry, is given in *Manual of Spectroscopy*, by Theodore A. Cutting (published in this country by Messrs. Wm. Heinemann Ltd.).

*Calibration.* When a number of characteristic lines and groups of lines can be recognized the scale may be engraved. A strip of millimetre-squared paper is pasted along the curved sheet of perspex about half a centimetre from its lower edge. The centimetre lines are numbered, say, from 0 in the extreme violet to 20 in the extreme red, for a first order spectrum formed by a lens of focal length of about 100 cm. When the internal illumination of the perspex is switched on, these numbers and the millimetre divisions between them can easily be seen in the eyepiece. Several substances are then volatilized in the arc one after another and the positions of chosen lines or groups of lines which are regarded as characteristic, such as lithium 6708, the orange manganese triplet, the sodium doublet, groups due to calcium, magnesium, chromium and zinc, and others selected by the operator, may be read on the millimetre scale and recorded. The perspex is then removed from the spectroscope and the positions of these characteristic lines or groups are engraved, together with the name of the element to which they are due, by means of a sharp instrument such as a stout needle mounted in a wooden handle. The writing in of the symbols of the elements as well as the engraving of the lines should be performed with great care with the help of a hand magnifier. In this way the positions of the most conspicuous and persistent lines of the common elements may be recorded and, if any of them are present in a mineral, they can at once be recognized. Other elements can soon be identified against this known background. It is also possible, with a little experience, to decide whether a particular element is present as a trace or in considerable quantity.

### (2) X-RAY SPECTRA

Following upon the discovery of M. von Laue that X-rays would give diffraction patterns in suitable circumstances, W. H. and W. L. Bragg demonstrated the possibility of the reflection of X-rays at the planes parallel to the cleavage surfaces of crystals. An instrument was built on the lines of an ordinary spectroscope, except that the reflected beam of X-rays was detected by means of an ionization chamber. Much as a diffraction grating is used to measure the wavelength of visible light, so in 1913 Sir William Bragg measured X-ray wavelengths by means of diffraction experiments, using a crystal as a reflection grating. The measurement of wavelength depended upon a knowledge of the spacing of the particles constituting the crystal and this in turn depended upon Avogadro's number, the most reliable value for which was for many years that deduced from oil drop experiments. As an instance of the kind of argument used in this work we may take the deduction of the size of the unit cell of sodium chloride. X-ray experiments of the Laue spot type had led to the conclusion that the unit cell of rock salt consists of a face-centred cube, that is, the constituent atoms are arranged in the form of an open cubic lattice, sodium atoms alternating with chlorine atoms in each of three directions at right angles to one another. The distances of the atoms from their neighbours along these three axes are all equal, giving the structure illustrated :

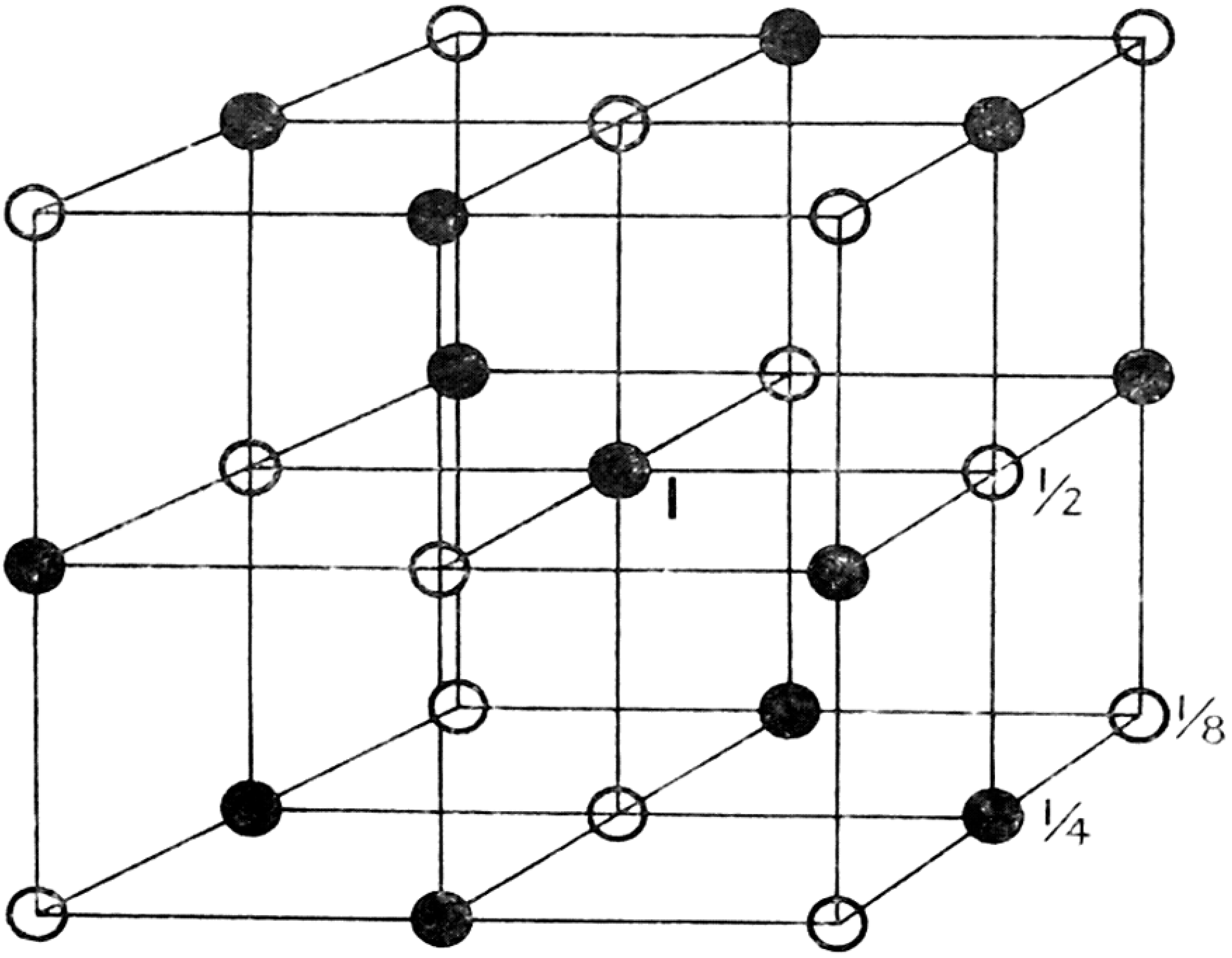


FIG. 58. Unit cell of sodium chloride. The white circles represent sodium atoms and the black circles represent chlorine atoms.

By the term unit cell is meant the simplest structure which will define the shape of the crystal as a whole and by the repetition of which a crystal is made up. A unit cell of rock salt contains four atoms of each kind, for each face in the figure must be regarded as being bounded by repetitions of the same structural arrangement. The sodium atoms at the corners of the cube in the figure are common to eight unit cells and thus each corner represents $\frac{1}{8}$ of a sodium atom. The sodium atoms at the centres of the faces are shared by one other unit cell only and thus each circle so placed in the figure represents $\frac{1}{2}$ of a sodium atom. Similarly, the black circles at the middle points of the edges are common to four unit cells and thus each represent $\frac{1}{4}$ of a chlorine atom. The black circle at the centre of the figure represents a complete chlorine atom which is not shared by another cell. We have thus :

$$\begin{aligned} &\text{White circles (say, sodium) } (8 \times \tfrac{1}{8}) + (6 \times \tfrac{1}{2}) &&= 4\text{Na} \\ &\text{Black circles (say, chlorine) } (12 \times \tfrac{1}{4}) + 1 &&= 4\text{Cl} \\ &\qquad\qquad\qquad\qquad\text{Therefore unit cell} &&= 4\ \text{NaCl}. \end{aligned}$$

Let $M$ be the weight in grams of 1 molecule of sodium chloride. Then the material making up one unit cell weighs $4M$ gm. Let the length of the edge of a unit cell be $a$ cm., from the centres of the atoms as depicted.

Let the density of solid rock salt be $\rho$ gm. per c.c.

Then the weight of the unit cube is $\rho a^3$ gm.

$$\rho a^3 = 4M$$

$$a = \sqrt[3]{\frac{4M}{\rho}}.$$

The evaluation of this length depends upon knowledge of the weights of the sodium and chlorine atoms. Hence it depends upon the weight of one hydrogen atom, that is, upon Avogadro's number $N$. As stated above, until recently the best value for $N$ was that derived from the value of $e$ obtained from oil drop work. The well-known Bragg relation connecting crystal spacing with X-ray wavelength is $n\lambda = 2a \sin \theta$, where $a$ has been found in the way just described. This was the earliest method by which precise information about X-ray wavelengths could be obtained.

In 1928 Bäcklin succeeded in measuring the wavelengths of X-rays by means of a ruled grating. Such a method need involve no more than the use of a travelling microscope to arrive at the grating constant, although optical methods are also available. Wavelengths measured by means of a grating were found to exceed those deduced from diffraction at crystal surfaces by 0·203 per cent. and it was thought probable that the error lay in the rather indirect estimates of crystal lattice spacings. These values depend on $N$ and ultimately, as shown above, upon the oil drop value for $e$. Doubt was therefore cast upon the accepted value of this fundamental constant and redeterminations of the viscosity of air showed that the figure accepted by Millikan and others was in error to the extent of about $\frac{1}{2}$ of 1 per cent. The corrected value for $\eta$ and redeterminations of $e$ have given the present-day value of $4{\cdot}802 \times 10^{-10}$ e.s.u., which is in accord with X-ray measurements by means of a ruled grating. The best value of $N$ from ruled grating X-ray measurements is

$$N = (6{\cdot}0226 \pm 0{\cdot}0015) \times 10^{23} \text{ per gm. mol.}$$

Also in the year 1913 H. G. J. Moseley undertook an investigation of the characteristic X-radiations of thirty-eight solid elements, using a photographic method of recording the X-ray spectrum lines. He found a linear relationship, not between atomic weights and the square root of the frequencies of corresponding spectrum lines, but between $\sqrt{\nu}$ and the ordinal numbers which must be given to the elements when written down in order of their atomic weights, starting with hydrogen. These are the atomic numbers and have a more fundamental significance than atomic weights, for each represents the net positive charge on the nucleus of an atom, or alternatively, the total number of planetary electrons which the atom has when uncombined and in the electrically neutral state.

It is generally recognized that Moseley's discovery of the simple relation that exists between the X-ray spectra of the elements, except the lightest, which he was unable to observe, was a landmark in the progress of atomic theory, but no effort is usually made in schools to demonstrate the phenomenon upon which this important generalization depends. Yet many schools possess some sort of X-ray equipment which can be adapted for the purpose and the dangers attending its use can so easily be eliminated by proper experimental arrangements that there is no excuse for failing to show pupils how X-ray spectra can be produced. It is not suggested that time or facilities will be available for the quantitative work necessary to establish Moseley's law, but a spectrum showing some of the characteristic lines of the target metal of the X-ray tube can be photographed with an exposure of ten or fifteen minutes, only very simple apparatus being necessary. Of course, if the critical excitation potential cannot be reached no results will be achieved.

The X-ray spectrometers of Bragg, or modifications of these, employ slits to define the X-ray beam, resulting in such low intensity that long exposures are required to photograph the spectra. The adjustment of such a system and the exposure will therefore as a rule take up a good deal of time and will not be suitable for demonstration purposes. The method of Mlle. Cauchois, which employs the focussing property of bent crystalline sheets, is very easy to set up and the adjustments are not critical, unless the maximum possible sharpness of the lines is required. A rectangular beam of X-rays 2 cm. × 1 cm. may be used, the resulting intensity of the lines being sufficient to make photography possible with an exposure of ten or fifteen minutes. Plate VIII is reproduced from photographs of the $K$ spectrum and part of the $L$ spectrum of molybdenum, taken with an exposure of fifteen minutes, using a 10-inch coil and the X-ray tube described on pages 70–75 above. The filament current was 5 amperes.

The focussing property of a bent crystal is well known, as is that of the optical concave diffraction grating, but the complete theory is too mathematical to be given here. The crystal, which may be mica, is bent on a radius greater than 20 cm. and the crystal planes, which must not be confused with those parallel to the surface of the mica, make equal angles with the radii of the circle. Radiation of a given wavelength incident on these planes is reflected from them and focussed at a point on the circumference of a circle which has half the radius of that of the bent crystal and which touches it at its middle point. Fig. 59 is adapted from *X-rays* by Worsnop and Chalkin (Methuen & Co. Ltd.), p. 37.

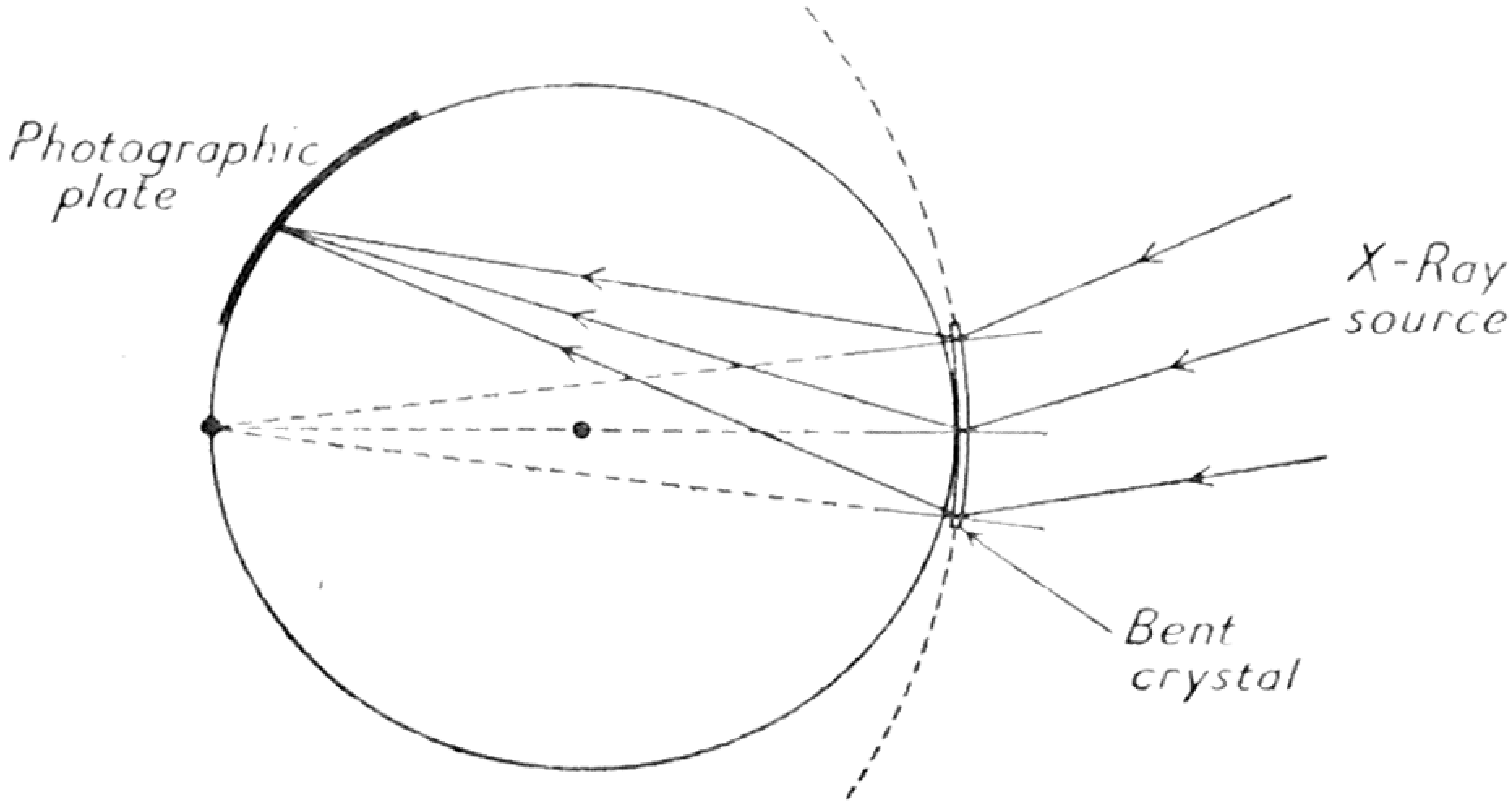


FIG. 59. Diagram illustrating the focussing property of a bent crystal. The radius to which the mica is bent is twice that of the photographic film.

The apparatus is very simple to make and to use. Since there are no slits the adjustment for direction is very simple and can be carried out by means of a fluorescent screen. The crystal holder may be a piece of lead sheet 6 cm. square and some 5 mm. in thickness. In the centre a rectangular hole 2 cm. × 1 cm. is cut. The lead is then hammered gently to a known curvature on a suitable anvil, such as a flywheel of 20–30 cm. radius. This gives a smooth curve of sufficient accuracy. A piece of mica about 0·1 mm. thick is cut to cover the aperture, but the direction of the crystal axis will probably be unknown and must be found by taking an X-ray photograph. As the mica is pseudo-hexagonal the first direction tried will give lines which are not more than 30° from the vertical and a single correction should be sufficient to give lines which are perpendicular to the length of the spectrum. When the required direction has been found, the mica may be firmly fixed to the lead sheet in such a way as to ensure that it takes the curvature of the lead. The crystal holder is then fixed perpendicularly to a baseboard and a movable arm of length equal to one half of the radius of curvature of the crystal carries the photographic film. The point about which the film holder rotates is the middle point of that radius of the crystal which passes through its middle point. The film holder is a vertical lead screen with a slit about 10 cm. × 2 cm. cut in it and is bent with a radius of curvature equal to one half of that of the crystal, the edges of the lead screen being bent over so that an X-ray film envelope can be inserted. The spectrometer is set up so that the direct beam through the crystal does not fall upon the film and the X-ray tube is allowed to run for 10 or 15 minutes. Kodak *Industrex D* X-ray film, ready wrapped in an envelope, is very suitable and can easily be bent to the curvature of the film carrier. The film is developed in the usual way, except that as it has emulsion on both sides, a T-piece of glass rod should be placed in the developing dish to allow access of developer to both surfaces. The developed film may be rephotographed by contact with a slow plate such as Kodak B20, giving about one second

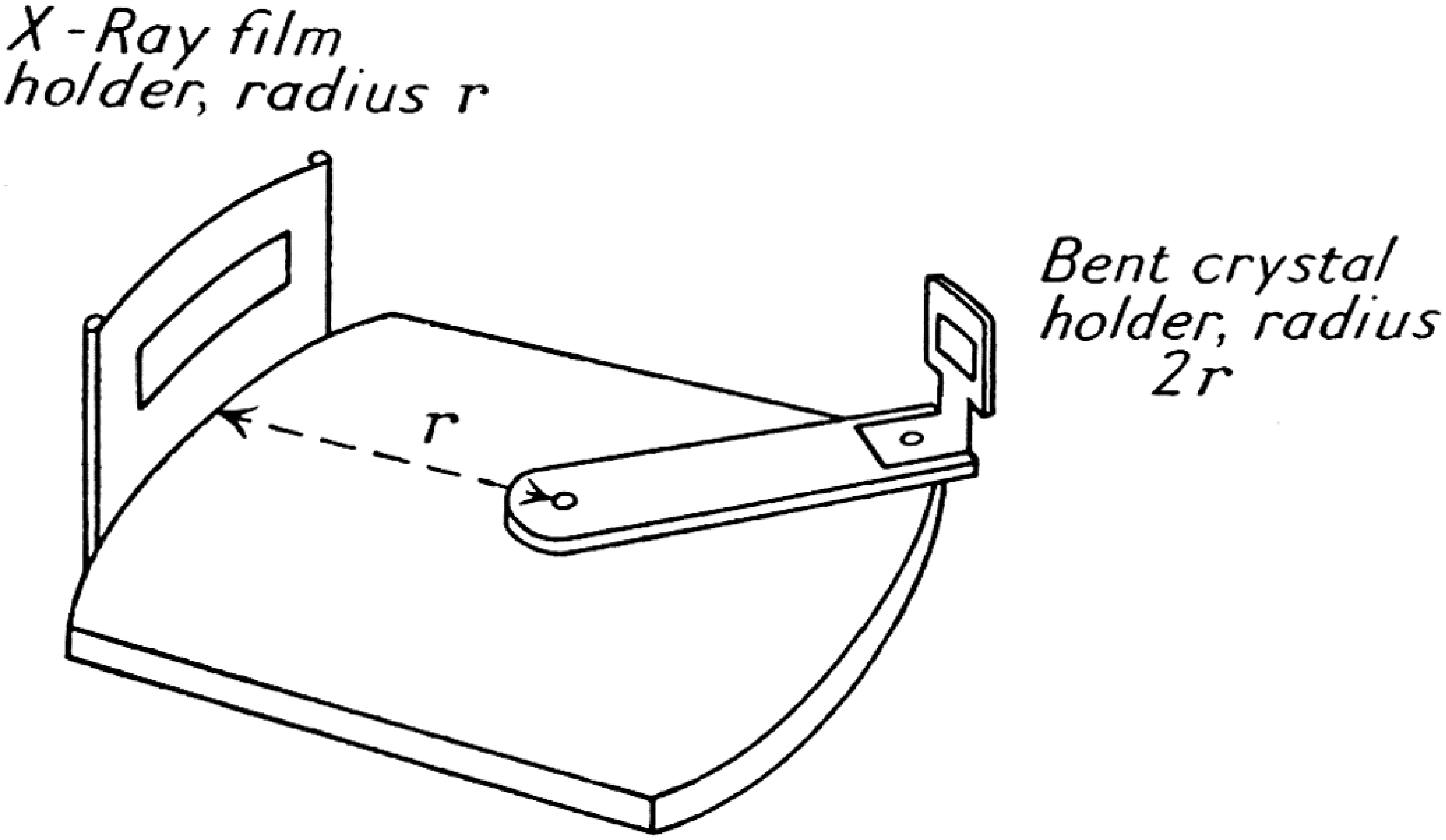


FIG. 60. Simple apparatus for building the bent crystal and X-ray film for photographing X-ray spectra.

exposure at a distance of 8 feet from a 100-watt tungsten lamp. Prints will then show the lines of the *K* or *L* spectrum according to the position of the plate carrier during exposure to the X-rays. It should be noted that these spectra will not appear unless the potential applied to the X-ray tube is sufficient for the purpose. Plate IV B was taken with a 10-inch induction coil. The apparatus employed is illustrated in Fig. 60.

Since the X-ray tube is demountable, the anticathode metal may be changed and the X-ray spectra of various metals may be compared, but it is not intended here to do more than to show that the lines can easily be formed. Pupils will soon pass from school to the University, where precision apparatus is available and measurements can be made. The work upon which Moseley's law has been founded has been verified time and time again and it is only the fundamental phenomenon of the X-ray line spectrum that is described here. Further work can be undertaken if time permits.

The inferences from the photographs obtained are indirect but are of high probability. The separation of the spectral lines giving a characteristic pattern for each element is evidence of a discontinuous structure within the atom and is additional to the evidence derived from optical spectra. The contemplation of these effects leads to the conclusion that the atoms of the different elements are built upon some simple plan. It remains to interpret the evidence.

# APPENDIX

## NAMES AND ADDRESSES FOR OBTAINING MATERIALS

**Intermediate Sealing Glasses.** These should be used for beading when sealing metals to borosilicate glasses.

(1) *Kodial*, for molybdenum or Kovar.
Plowden and Thompson Ltd., Dial Glassworks, Stourbridge, Worcs.
(2) *G.S.*3 (*G.S.B.*), for Kovar.
Chance Bros. Ltd., Glass Works, Smethwick 40, Birmingham.
(3) *Intasil* (*G.S.D.*), for tungsten or molybdenum into Hysil.
Chance Bros. Ltd., Glass Works, Smethwick 40, Birmingham.
(4) *W.*1, for tungsten into Pyrex.
General Electric Company Ltd., Magnet House, Kingsway, London, W.C.2.

### Metals

(1) *Dumet*, *i.e.*, copper-clad nickel-iron wire.
Duram Ltd., Thanet House, Strand, London, W.C.2, or R. G. McLeod Ltd., Lavina Grove, London, N.1.
(2) *Tungsten* wire or sheet.
*Molybdenum* wire or sheet.
Murex Ltd., Rainham, Essex.
(3) *Kovar* wire.
George and Becker & Co. Ltd., 17–29 Hatton Wall, London, E.C.1.
(4) *Telcoseal* wire.
Telegraph Construction and Maintenance Co. Ltd., 22 Old Broad Street, London, E.C.2.
(5) *Nilo* wire.
Henry Wiggin & Co. Ltd., Wiggin Street, Birmingham 16.
(6) *Palladium* tubes.
Johnson, Matthey & Co. Ltd., Hatton Garden, London, E.C.1.

### Vacuum Equipment

(1) *Everett's tap grease and waxes.*
H. J. Everett, Park Gate Pharmacy, Swanwick, Hants.
(2) *W.E. wax, tap grease, needle valves, silicone oils, etc.*
W. E. Edwards & Co. Ltd., Lower Sydenham, London, S.E.26.
(3) *Phosphors.*
Derby & Co. Ltd., 62 Cheapside, London, E.C.2.

## Various Items of Equipment

(1) *Short-range telescopes.*
W. G. Pye & Co. Ltd., Granta Works, Cambridge.
(2) *X-Ray films and nuclear track plates.*
Kodak Ltd., Kodak House, Kingsway, London, W.C.2.
(3) *Silica tubing and rod.*
The Thermal Syndicate Ltd., 12/14 Old Pye Street, Westminster, London, S.W.1.
(4) *Replica plane gratings, slits and eyepieces.*
R. & J. Beck Ltd., 69 Mortimer Street, London, W.1.

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# INDEX

ALUMINIUM, 11, 15, 39
*Andrade, E. N. da C.*, 91
Annealing, glass to metal seals, 23, 34
  internal seals, 24
Atomizer, 72
*Avogadro's* number, 56ff., 79, 82, 124

*Bäcklin*, 124
*Balmer*, 116
*Becquerel, Henri*, 81
Borax, fused, 23, 32, 111
*Bragg, W. H.*, 122
*Bragg, W. L.*, 103, 122
*Brown, Robert*, 56
Brownian movement, Ch. VI, 74
*Bunsen and Kirchoff*, 116

CARBON DIOXIDE, absorption of, 17
  discharge in, 29
Cathode rays, 6, 7, 15, 16, 37
*Cauchois Mlle.*, 126
*Chevalier*, 56
*Cockcroft and Walton*, 52
Colloidal silver, preparation of, 61
*Crookes*, 6
*Crookes* dark space, 7, 14

DIFFRACTION GRATING, 103, 115, 118, 124
Diffusion pump, cleaning of, 20, 25
  working substances, 18
Discharge tube, demountable, 32
  design of, 7ff.
Dumet, 9

*Einstein*, 57ff.
Eyepiece, *Ramsden*, 118

*Faraday*, 6, 67
*Faraday* dark space, 6, 13
Filament, tungsten, 32ff.
Fluorescent screen, 40, 46, 54, 112, 113
*Franklin, Benjamin*, 67
*Fraunhofer*, 56, 115
*Friedrich and Knipping*, 103

GAMBOGE, 57, 60
Gases, absorption of, 16
*Geissler*, 6
Glass, borosilicate, 10
  soda, 10
*Goldstein*, 6

*Häuy, Abbé*, 105
High tension wires, 13
*Hittorf*, 6, 7

*Laue von*, 102, 122
Liquid air, use of, 16, 17
*Lister, J. J.*, 56
Lithium metal, 52, 54

MAGNETIC FIELD, 37, 46
*Maxwell*, 67
*McLeod* gauge, rubberless, 26
Mica, bent crystal, 126
  window, 53
Microscope objectives, 56, 62
*Millikan*, 69ff.
Molybdenum, sheet, 44, 110, 111, 126
  wire, 10, 11, 23, 32
Monazite, 87
*Moseley*, 125

NEEDLE VALVE, 45, 46
*Newton*, 115

Nichrome, 23, 25, 112
Nickel, sheet, 15, 39, 110
Nickel chromium iron, 10
Nilo, 9

PALLADIUM TUBE, 30, 45
*Perrin*, 7, 57ff.
Phosphor, 37, 40
Phosphorus pentoxide, use of, 12, 21, 46
*Plücker*, 6, 7
Polystyrene, 84
Positive rays, 7, 15
Projection lantern, 86
Protons, 52
Pump, diffusion, 11, 14, 18ff., 29
  *Gaede*, 12
  Geryk, 8, 11, 14, 16, 22
  Hyvac, 12, 14, 22

QUICK RELEASE VALVE, 92
Quartz, bubbles in, 65

RADIUM, 51, 81f., 93, 97
*Röntgen*, 102
*Rowland*, 116
*Rutherford*, 51f., 82
Rutile, 60

SEALING GLASSES, *Chance's*, 10
  G.E.C., W.1, 23
  Kodial, 10, 11, 23, 32ff.
*Sidot's* blende, 82
Silicone oil, 18, 20, 112
Silver solder, 15, 23
*Soddy*, 51, 89
Space charge, 14, 113
Spectroscope, design of, 115
  use of, 31
Spinthariscope, model, 87ff.
  use of, 54

*Stokes*, 75, 115
*Stokes'* law, 76
*Stoney, Johnstone*, 67, 68
Strain-viewer, use of, 23

TELCOSEAL, 9
*Thomson, J. J.*, 14, 36, 43, 68
Thorianite, 87
Thorium, 51, 81, 98ff.
  C, 90, 93, 99
  dioxide, 35
*Townsend*, 68
Tungsten, sheet, 110, 111
  wire, 10, 23

URANITE, 87
Uranium, 51, 81, 99

VACUUM WAX, 15

WATER CELL, use of, 62
*Weber*, 67
Willemite, 82
*Wilson, C. T. R., and Wilson, J. G.*, 95
*Wilson, H. A.*, 69
Wire, cleaning of, 11
  Dumet, 9
  molybdenum, 10, 11, 23, 32
  nichrome, 23, 25, 112
  nickel chromium iron, 10
  Nilo, 9
  Telcoseal, 9
  tungsten, 10, 23
*Wollaston*, 115

X-RAYS, 79, 80, 81, Ch. IX
X-ray, tube, making of, 108ff.
  vacuum, 14
Xylene potentiometer, 107

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